**MASTER OF SCIENCE BY RESEARCH**

# The migration of heavy metals from urban surface dust in simulated grass swales

## an evaluation of grass species aimed to assist retention of particulates in SUDS devices

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*Award date:*
2010

*Awarding institution:*
Coventry University

# The migration of heavy metals from urban surface dust in simulated grass swales: An evaluation of grass species aimed to assist retention of particulates in SUDS devices

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A thesis submitted in partial fulfilment of the University's requirements for the Masters degree (MSc.) by Research in Water Science

June 2010

COVENTRY UNIVERSITY

# Abstract

Urban environments possess large areas that are covered in impermeable surfaces, leading to problems with buildup of non-point pollutants on surfaces as well as increased volumes of runoff produced with rainfall events. Sustainable Urban Drainage Systems (SUDS) offer a means to mimic natural drainage processes to deal with the quality and quantity of runoff at the source. Vegetative SUDS such as swales and filter strips are two such systems that can be used to help manage drainage, removing the suspended solids and promoting infiltration of runoff into the soil. This study aimed to investigate whether particular grass species would be more suitable in these surfaces than others both in removing pollutants (e.g. Heavy Metals) and reducing flows.

A pot based pollutant retention study was conducted using processed street dust from central Coventry as a simulated pollutant to be applied in different quantities to the grasses. Analysis was then conducted on compost cores, roots and shoots for heavy metals (Cd, Cu, Ni, Pb & Zn). Street dust was shown to be mainly concentrated in the top layer of compost for all the grass species with only the fine material migrating through the profile. None of the heavy metal concentrations in the roots were influenced by the addition of street dust whereas ANOVA analysis indicated that street dust treatments caused significant differences in heavy metal concentrations in shoots. A pattern of accumulation was illustrated by decreases in heavy metal concentrations in the compost which resulted in increased shoot concentrations. Development of root systems on or near the surface of the pots was possibly a reason for increased uptake of heavy metals by some species. Overall *Agrostis canina* and *Poa pratensis* showed the greatest accumulations compared to their controls although *Agrostis capillaris syn.tenuis* and *Agrostis stolonifera* also showing accumulation potential.

Hydraulic trials involving the use of seed trays to mimic vegetative surfaces were subjected to simulated runoff to examine if particular grass species encouraged infiltration. The results showed that throughflow and hence infiltration was related to the distance travelled along the tray. The different species showed no significant difference between each other regarding encouraging infiltration. Overall the Bent species of grass (in particular *Agrostis canina*) were shown to promote more throughflow. Based on the two trials the

Bents (in particular *Agrostis canina*) and *Poa pratensis* were deemed to be suitable species worthy of further investigation on a larger scale.

# Acknowledgements

There are many people I would like to thank for their generous contributions towards making this research possible. Firstly I would like to thank my supervisory team Dr. Sue Charlesworth and Dr. James Bennett for their constructive criticisms, support and patience while I completed this thesis. I offer many thanks to Dr David Lawson of STRI for supplying materials and knowledge to get this project out of the starting blocks. I also would like to thank Richard Collins and Anne Nuttall for their support in the laboratory, helping me with techniques I was not familiar with but most importantly always being there in my hour of need. A huge thank you to my family that have always encouraged me and understood the difficulties and I hope that you are all proud of what I have achieved. Last but not least, I would like to thank my wonderful partner Emma Williams for her unconditional support and encouragement that carried me through the more difficult times. Emma you were the shining beacon of light at the end of a very long tunnel.

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# 1.0 Introduction

## 1.1 Drainage: An Historical Context

Historically drainage has been based upon underground pipes that are designed to convey runoff away as quickly as possible to avoid flooding. Traditionally there was one piped sewer for both clean and waste water although in the last 50 years a two piped system has emerged allowing untreated water to be pumped to a water treatment plant and surface water to be directed to a local water course. However, these systems are susceptible to collecting pollutants and transferring them directly from an urban surface to a water body (Woods-Ballard et al. 2007:42). There is also an issue with pipe drainage systems inevitably not being able to contain and deal with extreme and excessive rainfall, overflowing and causing flooding. Piped drainage is not sustainable or economically viable to manage extreme rainfall and when sewers reach their capacity may convey sewage above ground (Balmforth et al. 2006:23).

Drainage issues are also exacerbated by factors such as land use. Rural areas, which have notably less urbanised landscape, have a larger area for runoff generated by rainfall to be infiltrated into, reducing the volume. Other processes such as evapotranspiration off vegetation further reduce the volume of runoff that flows across the surface (CIRIA 2000; 2001). Development of land causes a reduction in natural vegetated lands and therefore less infiltration and evapotranspiration. However, development, also known as urbanisation has a number of other negative affects upon drainage systems which are discussed in the next section.

## 1.2: The Impact of Urbanisation

Urbanisation is defined as the process of people moving from a rural area to a developed area with a larger increase in housing density and the reduction in natural areas (Balmforth et al. 2006:69)**.** Free draining land is replaced with surfaces such as roofs and paving that are often drained with piped drainage (Woods-Ballard et al. 2007: 42). With a decrease in natural area there are extensive areas of impermeable surfaces which remove the natural processes of absorption and saturation of soil (Balmforth et al. 2006:69). Lack of vegetation also reduces the amount of rainfall or runoff that is intercepted and slowed. With surface waters having limited infiltration and natural storage effects not being replicated in urban environments, large amounts of surface runoff flow into local water courses or sewage systems (CIRIA, 2000, 2001). With piped drainage having a limited capacity for water storage smaller rainfall events in urban areas are therefore more likely to cause flooding than in rural areas where heavier, more intense rainfall would be needed for similar effects (White and Howe, 2002). A comparison between a rainfall event in a rural and urban environment is shown in Figure 1.1 to illustrate the effect that urbanisation has on runoff production.

***Figure 1.1****: Urban and Rural Hydrograph*

(Sourced: Woods-Ballard et al. 2007:1-5)

Although flood risk is a major problem, surface runoff also transports urban pollutants that are deposited on hard surfaces such as pavements into local water bodies and influences their water quality. The Water

Framework Directive (European Union, 2000) aims to achieve good water quality in UK bodies by 2013. Approximately 25% of river lengths and 14% of groundwater are at risk of failing standards for water quality due to diffused urban sources of pollution (Wood-Ballard et al. 2007:42). With urban areas having increased human activities such as traffic and industrial activity there is an increase in the quantity of pollutants being deposited on hard surfaces (Patel 2005). Therefore a drainage system with the ability to not only to reduce and manage surface rainwater but improve water quality would be extremely valuable.

Climate change is also an important issue for urban drainage. It is predicted that by the 2080s winters will be milder but wetter with more frequent and extreme rainfall. Summers will also tend to be hotter with more extremes conditions such as heat waves. The effects this will have on water quantity and quality is that in the drier summers there will be an increased build up on hard surfaces of pollutants such as heavy metals. The drying of the soil will also inhibit absorption of water and hence prompt more runoff. When runoff is prompted the build up of pollutants will be transferred to receiving water bodies, deteriorating their water quality (Woods-Ballard et al. 2007:47). The resulting effects on hydrological conditions and hydrological responses of a watershed will be further exaggerated by urban environments and their impermeable surface (Burrell and Arisz 2006:1).

With the evidence that urban areas can promote conditions that allow increased quantities of runoff and harmful pollutants increases in building activity will worsen the hydrological issues even further. The Baker Report (2004) stated that it is recommended that 325,000 new houses are built each year to accommodate population growth and to keep house prices from rising dramatically (Ellis et al. 2004a:245). Development can often be in close proximity to flood plains, areas that are at risk of inundation. Approximately two million properties are built in flood risk areas in England and with a further 3.8 million homes are needed by 2021; the number of homes at risk is likely to increase (White and Howe, 2002). Urbanisation has in fact increased the average housing density from 15-20 houses per hectare in the 1930s to today where the average housing density in an urban area is 30-50 houses per hectare (Ellis et al. 2004a:246). With these denser urban populations and their negative effects on water quantity and quality a drainage system is needed that can provide sustainable solutions to these issues.

## 1.3 Tackling the Hydrological Effects of Urbanisation

In 2004 DEFRA set out to analyse the pressures upon water resources and develop a government strategy for land use and management of water resources for the future within its report, *Making Space for Water* (CIRIA 2005:2). Sustainable Urban Drainage Systems (SUDS) are a range of techniques that DEFRA promoted which would improve environmental management of water resources by storing them with methods such as rainwater harvesting, as well as offering a reduction in the quantity of pollutants that would be transported to water bodies. SUDS also help fulfil other government objectives on biodiversity and amenity (Woods-Ballard et al. 2007:48). The report also proposals the government was made to encourage further development of SUDS. SUDS have been largely implemented in Scotland with the Scottish Environmental Protection Agency (SEPA) developing strategies in 1993 that allowed by 1999, 201 schemes to be implemented, and by 2001 more than 767 (Kirby 2005:119). SUDS are now being more widely used in England with projects such as that at Upton, Northampton, which is the site of a sustainable development that forms the first part of a major expansion of Northampton (CIRIA 2007). With SUDS being increasingly implemented in the UK and approximately 21% of the West Midlands front gardens being more than $^{3}/_{4}$ paved, it represents an opportunity to research SUDS methods that could be applied and lead to up to a 50% reduction in runoff (Royal Horticultural Society, 2006). This study aims to look at particular aspects of SUDS that could be applied to urban areas such as Coventry, and determine their ability to improve and retain pollutants and runoff that might be generated by urbanisation.

# 2.0 Literature Review

This chapter focuses in more detail on the aspects of drainage systems discussed in the introduction, including an overview of sustainable urban drainage systems (SUDS) and their performance as well as discussing the types and the sources of urban pollutants they would deal with. This culminates in a focus on one type of SUDS device, developing an overview of its features as well as possible gaps in knowledge that allows a set of research aims to be constructed in order to satisfy the research question.

## 2.1 - SUDS

Due to the negative aspects of conventional drainage systems and the impact that urban areas have on the environment, urban drainage is becoming more focussed on public hygiene, flood protection and environmental protection. SUDS are seen as an engineered solution to these issues as they provide a more sustainable method of dealing with drainage (Chocat et al. 2007: 274). The design behind SUDS involves drainage installations that mimic natural processes such as infiltration which is designed into systems that are to mitigate not only the quantity of stormwater but also its quality. The philosophy behind SUDS can be described using the SUDS triangle shown in Figure 2.1, where quantity, quality and amenity values are given equal importance whereas in a conventional drainage system quantity would have much larger significance than the other factors. SUDS consider all three areas in an effort to make the built environment more natural (Martin et al**.** 2001:3; Kirby, 2005:115).

***Figure 2.1:*** *The SUDS Triangle*
(Source: Martin et al. 2001)


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Tackling all three of the areas in Figure 2.1 makes SUDS a more holistic drainage method. Like conventional drainage, SUDS can be used to divert and transport the excess water to another location or SUDS. Unlike conventional drainage, SUDS also allow infiltration on site; this is known as source control. Discharges downstream can be controlled to a certain extent (Kirby, 2005:115). SUDS include numerous types of SUDS devices which can be either non structural or structural. Non structural SUDS techniques would be education or incentive based, designed to modify human behaviour in a water management sense and was not the focus of this study (Apostolaki et al. 2006). Of more relevance are the structural SUDS, including installations such as infiltration trenches, green roofs, soakaways, swales and retention ponds (Woods-Ballard et al. 2007:40-41). These devices are engineered to mimic or allow natural processes such as infiltration using as many natural resources such as vegetation as possible. By having a more nature orientated system many of the issues regarding quantity and quality of runoff that exist with conventional drainage are removed (Stovin and Swan, 2007:207).

Each technique has different strengths and weaknesses and therefore has to be used in conjunction with others in order for the whole approach to be fully effective. For example, filter strips are effective at removing suspended solids but are poor at reducing peak flows (Woods-Ballard et al. 2007:231). This creates what is known as a management train. An example of a SUDS management train is shown in Figure 2.2 which divides an area into sub catchments. Each sub catchment has its own characteristics and therefore would require different SUDS devices to deal with its drainage. This means that water is dealt with on site and reduces the volume of water that needs to be managed. The management train then goes to a larger scale with larger, regional sites. This is designed so that if water does need to be conveyed to another site it will be cleaner and therefore require less attention. In a perfect system, water would be dealt with on site and therefore reduce the pollution that is conveyed to local watercourses as well as reducing quantity (Kirby, 2005). Ensuring that the correct devices are employed in the correct manner is the only way to create a strong SUDS management train and therefore a successful drainage network that can handle the identified water quantity and quality issues (Martin et al. 2000). However, some aspects of devices such as vegetated surfaces, in particular the species of grasses that are used, need scientific justification so that better design decisions can be made.

***Figure 2.2:*** *The SUDS Management Train*

(Source: Kirby, 2005:116)

## 2.1.1 - SUDS Advantages and Uncertainties

Like any drainage system, SUDS are perceived to have both advantages and uncertainties which are outlined in Table 2.1. SUDS can have a large number of benefits and if applied correctly, will have a positive bearing on the costs of treating stormwater and dealing with the damage of flooding. However, Table 2.1 also shows that SUDS have a number of uncertainties that act as barriers to their implementation; these include ownership, maintenance, design and responsibility (Wood-Ballard et al. 2007; Kirby, 2005).

Vegetated SUDS in UK can suffer from confusion over ownership. With swales being designed to be both over and under land systems they do fall into a difficult, grey area of ownership with neither the council nor local water utility companies wanting full responsibility for their upkeep and maintenance. This is an issue which, in Scotland, has been solved with a framework agreement that outlines the responsibilities of SUDS (Kirby, 2005:119). However, swales and filter strips are advantageous as they are cost effective compared with other SUDS devices in terms of both retrofit and new installations (Wilson et al. 2004:274). Vegetated surfaces such as swales offer a fairly cheap option for flow conveyance and source control compared to other methods (Wood-Ballard et al. 2007:498); although this does not take into consideration other characteristics such as land availability and land cost. It also does not take into consideration that some sites may not have suitable soils, geology, topography or space to house a vegetated SUDS device (Balmforth et al. 2006:206; Wood-Ballard et al. 2007:255-256). Costs would also differ with new developments; however swales would still be lower cost than most other devices, making this option one that is likely to be considered over more expensive alternatives such as filter drains or permeable paving (Stovin and Swan, 2007:209).

***Table 2.1:*** *Advantages and Uncertainties of SUDS*

| Advantages | Uncertainties |
|---|---|
| Reduces the rapid influxes of stormwater into water courses, lowering peak flows into water courses and sewers (Wood-Ballard et al. 2007). | There are few long term studies of SUDS and their performance (Kirby, 2005:118). |
| Reduces the quantity of stormwater (Wilson et al. 2004:29). | Uncertainty in the long term operational costs of SUDS devices (Chatfield, 2007). |
| Deals with stormwater at the source (Kirby 2005:115). | Issues with ownership and responsibility of the different elements that makes up SUDS (Kirby, 2005:118). |
| Improve stormwater quality compared to traditional drainage systems (Wood-Ballard et al. 2007). | Require regular maintenance to achieve full potential (Wood-Ballard et al. 2007). |
| Reduce the amount of suspended sediments carried in runoff SUDS reducing blockages of piped drainage systems (Wood-Ballard et al. 2007). | |
| Reduces the operational costs of sewers by reducing the number of combined overflows operating and discharging into watercourse (Wood-Ballard et al. 2007). | |
| Can be built into new developments or retrofitted to fit existing developments (Stovin and Swan, 2007:207). | |
| Can improve soil conditions on contaminated or brownfield sites (Wood-Ballard et al. 2007:77). | |
| SUDS management train can be used to convey and clean stormwater. This makes it easier to deal with the non-point sources of pollution common in urban areas (Kirby, 2005:115). | |
| Improvement in amenity with the inclusion of more natural features (Kirby, 2005; Martin et al. 2001:3). | |
| Reduce costs and help achieve the criteria for the Water Framework Directive (European Union, 2000). | |

With cost being a major issue in deciding whether a SUDS device is adopted, a more effective swale would add to the benefits that SUDS devices already possess. Whilst there has been much research into vegetative surfaces, Escarameia et al. (2006:22) also identify a number of areas in which vegetative surfaces can be explored further. There is particular uncertainty over the pollutant removal capabilities of different grasses as previous studies have shown varying degrees of effectiveness that range from 40%-

90% reductions in heavy metals (Wilson et al. 2004:197). Examining the uptake of urban pollution with a variety of grass species would help identify those that are more efficient at removal of pollutants. Grass species could then be used to target specific pollutants. It would also identify features of the grasses that may be advantageous and affect the performance of a swale. Accumulation of heavy metals in the shoots is not the only factor; for example different species may accumulate different amounts in the roots which would reduce the risk of heavy metals being available in hazardous quantities in the shoots. Different species could also have root developments that may aid the movement of suspended sediment that becomes settled. Understanding the growth and physiological effects of different species could highlight issues that could be applied to improving the performance of a swale.

Other than investigating pollutant retention characteristics, different grasses have different qualities that are worth considering when choosing to use different species. Wilson et al. (2004:206) suggests that grasses should be able to withstand wet and dry conditions along with reasonably high water velocities (1-2m/s), identifying perennial ryegrass and fescues as most suitable for swales in the UK. However, no quantitative reasons are given as to why these grasses are suitable or whether they have properties that would help in processes such as heavy metal uptake. Instead it states factors such as having a salt tolerance, rapid growth rate and tolerance to wet that make grass species suitable (Highway Agency, 2006). Also there appears to be a lack of information about species that have different sowing densities. CIRIA mention that fine growing grasses (blade densities of 600-1600 of grass per $0.09m^2$) increase filtration and are thus suitable for swales; however there is no mention of specific grass species that have this characteristic. For example, species of Bent grass grown at high seeding densities could achieve this and be perfect for swales, but have not been recommended (Wilson et al. 2004:206). Due to complicated experimental design and unavailable resources it would be difficult and expensive to test the removal efficiency of devices such as infiltrations trenches and soakaways. However, a more practical and achievable objective is to test the efficiency of individual grass species, providing a scientific and detailed analysis of which are more suited for swales and filter strips. This would include an examination of aspects discussed in this section such as how the different species accumulate heavy metals differently throughout the plant, as well as how different species could potentially affect the movement of settled sediment.

## 2.2 - Vegetated SUDS

Vegetated SUDS include devices such as swales and vegetative strips. Swales are defined as broad, shallow channels that have dense vegetation such as grass, covering the sides and bottom. There are three types of swale; a swale, an enhanced dry swale and a wet swale (Wood-Ballard et al. 2007:254).They are designed to reduce water velocity and therefore allow infiltration and evaporation (Kirby, 2005:116). Slowing the velocity of runoff will also allow the suspended solids in the runoff to be deposited, thus organic material and minerals can enter the soil (EPA, 1999; Kirby, 2005). Swales are also designed to convey, and can detain water for treatment often via check dams which are similar to barriers, placed at regular intervals and which greatly improve removal performance by dissipating runoff energy (Yu et al. 2001; Wood-Ballard et al. 2007:259). Filter strips work in a similar way and although they are not designed to attenuate flow, they can be used to drain areas (Martins et al. 2000:18). Once water has flowed into a vegetated SUDS a complex series of processes begin, Figure 2.3 shows the basic principle behind each of the devices.

***Figure 2.3:*** *Illustrations of a swale and filter strip system*

(Source: Martins et al. 2000:8)

### 2.2.1 Type of Swales

The three types of swale are illustrated in Figure 2.4. An enhanced dry swale has a filter layer of soil above an under drain which is designed to keep the swale dry for the majority of the time. The added advantage of a dry swale is that it will not become unsightly or generate odours. Wet swales are designed to act as partial wetland, where standing water is retained. Typical swales are simple grassed channels designed to convey runoff while reducing the quantity and improving the quality of runoff (Woods-Ballard et al. 2007:254).

***Figure 2.4:*** *Types of Swale*

(Source: Woods-Ballard et al. 2007:254)

Swale systems can be used in urban locations such as car parks and roads and are designed to remove pollutants from small storm events, generally a 1 in 2 or 1 in 10 year return period (Wood-Ballard et al. 2007:256). In dense urban areas they can have a dual purpose of being used to convey runoff or act as a store while the runoff is infiltrating into the soil. As storage is often impractical, devices are often used in conjunction with other techniques such as retention ponds that are better suited for storing excess water (Jackson et al. 2006). However, swales can also be used as standalone features especially if the catchments have small amounts of impermeable surfaces which generate runoff (Wood-Ballard et al. 2007: 251).

### 2.2.2: Removal Processes within a Swale

With runoff being diverted or flowing into swales, a number of processes are used to improve the quality and reduce the quantity of received surface runoff. Quantity issues are usually addressed by three processes; infiltration, detention/attenuation and conveyance (Woods-Ballard et al, 2007). However, regardless of the process, a proportion of the runoff and pollutants will always exit the swales (Deletic, 2001). The most desirable method is infiltration as it restores the hydrological process by allowing water to recharge the water table or feed base flows to local water courses (Woods-Ballard et al, 2007). Grass has a large roughness coefficient which prompts the slowing of runoff and increased infiltration (Deletic, 2001). However, the effectiveness of infiltration is dependent on other factors such as soil conditions and antecedent weather conditions. Detention and attenuation of runoff simply slows the water down causing a less severe storm peak, but does not reduce the volume (Wood-Ballard et al. 2007). Devices such as check dams can be included to aid in the detention of runoff by creating an artificial barrier which can slow runoff down by creating a pool behind (Yu et al. 2001). This also aids infiltration, allowing runoff time to infiltrate into the soil. Conveyance also transfers the runoff water from one location to another, although there would be a reduction volume due to other processes.

The quality of runoff is improved through a combination of physical, chemical and biological processes. These are listed below in Table 2.2.

***Table 2.2****: Removal Processes within a Swale*

Source: Wood-Ballard et al. 2007:52-53

Not all these processes are used for removing every pollutant with different pollutants being more successfully removed by particular processes. Table 2.3 shows a list of pollutant types and their main mechanism of removal.

**Table 2.3**: *Removal Mechanisms particular Pollutants*
(Source: Wood-Ballard et al 2007:53)

The improvement in water quality is related to a multitude of factors such as environmental conditions, with decreased performance due to conditions such as high runoff velocity, submerged or bent vegetation and frozen ground. In fact there is a decrease in both water quality and quantity performance in the winter months with the ground conditions not being as favourable for infiltration and hence a reduction in quantity of runoff (University of New Hampshire, n.d.). Vegetation is also often dormant and therefore might not have optimum cover, limiting the amount of sedimentation, filtration and plant uptake available.

## 2.3 – Performance and Design of Vegetated SUDS for Pollutant Control

The performance of grassed devices depends greatly upon the physical and chemical characteristics of the area and should therefore be reflected in the design and installation of the system. In order to produce guidelines for performance, research has been undertaken to assess the effectiveness of these systems, some of which is discussed in this section. However, much of this research has focussed on rural vegetated devices in agricultural or forested land. The comparison of results is difficult due to the varying nature of previous research (Deletic and Fletcher, 2006).

### 2.3.1 - Heavy Metals Removal Efficiency

A swale will remove total suspended solids (TSS), heavy metals and hydrocarbons effectively; however, it will be poor at removing nutrients and bacteria (Wilson et al. 2004:194). The extent to which pollutants such as heavy metals are removed is highly variable with poorly designed vegetated systems giving a bad representation of their removal potential. Factors such as the slope, length of swale and geometry will affect hydraulic retention time (HRT), affecting removal performance. Seasonal variations in rainfall can also affect performance by either flooding the vegetated surface or by causing drought, both of which can have negative effects on grass, by killing it. Heavy metal removal efficiency of swales and filter strips is summarised in Table 2.4, and reflects the principle pollutant removal mechanisms of trapping sediment in the vegetation, allowing filtering and absorption of nutrients either into the soil or systematic uptake by plants (Wilson et al. 2004:200). Therefore the majority of the removal of heavy metals and other pollutants are linked to removal of the suspended solids in runoff.

***Table 2.4:*** *Pollutant Removal Efficiency for Swales*
(Wilson et al. 2004:197)

| | Removal Efficiency (%) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **References** | **Median efficiency quoted by USEPA (2002)** | **Barrett, (1998)** | **Claytor and Schueler, (1996)** | **Walsh et al (1997)** | **Roesner et al (1999)** | **Highway Agency et al (1998b)** | **Winer, 2000** | **Schueler (2000)** | **Wilson et al (2004)** |
| TSS | 81 | 70 | 80 wet / 90 Dry | 60-83 | 80 | 60-90 | 38 | 81 | 60-80 Wet / 70- 90 Dry |
| Cadmium | 42 | - | - | - | 65 | | | 42 | 40-70 Wet / 80- 90 Dry |
| Copper | 51 | - | 40-70 Wet / 80-90 Dry | 50-90 | 50 | 50-70 | 32 | 51 | |
| Lead | 67 | - | - | - | 75 | 80-90 | 35 | 67 | |
| Zinc | 71 | - | - | - | 50 | 70-90 | 28 | 71 | |

## 2.3.2 - Performance at Removal of Suspended Solids

The removal of TSS is summarised in Table 2.4. The studies show that on average 60-90% of suspended solids are removed by swales; however this can be as low as 38%. Like the removal of heavy metals, removal of suspended solids depends on not only a well designed vegetated device which creates conditions allowing effective removal of solids from the runoff, but also factors dictated by the environment and location (Deletic, 2005). Thickness of the grass blades and hence density of the sward were highlighted by Deletic (2005) as a factor influencing sediment removal, something that is important when the primary purpose of vegetated surfaces is to slow surface runoff to promote deposition and infiltration (Wood-Ballard et al. 2007:253). The higher the density of grass, the greater the impact it will have on reducing the velocity of water flow (Han et al. 2005:1637). Blanco-Canqui et al. (2004) utilised different grass species to investigate how they might remove sediments, nitrogen and phosphorous. The length of the sward and also the presence of grasses reduced runoff by different amounts (See Table 2.5). Four different filter strips were created, each at eight metres long, the control (CCF in Table 2.5) was comprised of a cultivated fallow, whereas the other three filter strips were seeded with fescue grass (Fescue FS in Table 2.5), switchgrass barrier and fescue (B-Fescue-FS in Table 2.5) and a native plant filter strip (B-Native-FS in Table 2.5). Firstly Table 2.5 shows that the filter strips reduce the amount of runoff as it travels down the length of the strip, compared to the control (CCF). It also shows that the filter strips remove a large percentage (~97.8%) of the sediment that was applied within the first 0.7m compared to the control that only removed 28.7% of the sediment.

***Table 2.5****: Mean Surface Runoff and Sediment Reduction for Different Grassed Filter Strips*

Source: Blanco-Canqul et al. 2004:1673

This is verified by a study by Yu et al. (2001) in Taiwan and Virginia. The Taiwan swale was subjected to synthetic runoff whereas the Virginia runoff was monitored when subjected to storm events. Both showed that a more gradual slope helped with sediment removal. The conclusion from the data was that without check dams, grassed surfaces should not be on a slope of more than 3%. However, other studies show that swales can be effective with slopes up to 23% as long as flow is uniform (Deletic and Fletcher, 2006:262). Yu et al. (2001) also found that the length of swales had an impact on the removal of sediment. Deletic and Fletcher (2006) used two sites, one on the campus of Aberdeen University and another adjacent to a highway in Brisbane. When sediment was added to both in a semi controlled manner there was an exponential decay in the amount of sediment that was trapped by both swales along their length. This was especially true in the Brisbane swale where it exhibited large amounts of deposition in the first quarter of its length, with fine materials deposited depending on slow flow velocity. In fact flow velocity is critical to the deposition of material along a swale with faster flow velocities leading to deposition further down a swale. The likelihood of detaining pollutants is increased by using a longer swale or reducing flows (Yu et al. 2001). It is also important to note that geomorphological processes such as soil conditions have a considerable impact on all the other factors discussed in this section (Deletic and Fletcher. 2006).

### 2.3.3 - Hydraulic Performance of Swales

According to Wood-Ballard et al. (2007), grass filter strips are designed more for treatment of runoff (via removal of sediments) than attenuating flow rates. For grass filters there is limited available information on their hydraulic performance although this is influential on the level of pollutant removal that can be achieved. There are few studies of vegetated swale hydraulic performance in the UK but in Scotland two swales in Dundee have been monitored producing a mean reduction in peak flow of 1.2% for one swale and 52% for the other. This difference could be attributed to the fact that one of the swales was not finished and natural vegetation had not had time to become established. Regardless of this, mean lag times were slightly longer than that compared with roads, ranging from 12-14 minutes. Runoff was also prevented from leaving the swale for 24-50% of all storms (Wilson et al. 2004:187+198).

A study conducted by the Toronto and Region Conservation Authority (2006) showed the recorded runoff volumes for conventional asphalt, permeable paving and swales with 9 rainfall events. The total rainfall was measured at 52.8m$^3$, and swales had the highest reductions in volumes of runoff out of the three surfaces of 22.5m$^3$. This was mainly due to their ability to allow runoff to infiltrate into the soil and be accumulated by grasses. When the soil was saturated the water would pond on the surface turning into runoff, indicating that vegetated surfaces such as swales have potential for hydraulic retention. In comparison conventional asphalt and permeable paving only reduced the volume of runoff to 44m$^3$ and 39m$^3$ respectively.

However, Colwell et al. (2000) found that hydraulic performance of swales can be poor and hydraulic residence time (HRT) can be less than the 9 minutes recommended by CIRIA. From the twenty swales monitored they found that four had an HRT of over 9 minutes and five had an HRT of less than 5 minutes. The data showed that only the slope had a significant correlation with HRT which does not support the suggestion that vegetation density has a strong influence on HRT. Generally, vegetated surfaces in swales are known to be effective at reducing peak flows compared to impermeable surfaces, releasing the runoff slowly over a period of many days. With enough capacity, swales could reduce peak flow by up to 95% (Toronto and Region Conservation Authority, 2006).

HRT is often highly variable with differences being noted in winter and summer with an average reduction in winter of peak flows sometimes as low as 37% which may be due to frozen, flattened or bent grass (University of New Hampshire, n.d.). Soil conditions are also a factor in the efficiency of vegetated surfaces. Deletic and Fletcher (2006) illustrated this with a study using artificial flow on two grassed surfaces. The first experiments showed higher infiltration rates due to the soil becoming increasingly saturated, it was however, noted that fine sediment could clog surface pores, which would diminish infiltration, increasing the outflow rate from the vegetated surface. This showed that soil conditions and weather could be more important than the grass species used (Deletic and Fletcher, 2006:268). If the design of a vegetated surface is correct, runoff could be retained and the residence time would be long enough to allow infiltration to occur whilst one study by Colwell et al (2000) showed no significant relationship between HRT and grass type, it does not necessarily mean this is always the case. Deletic (2005) states that grass species does seem to be an important factor as different grass species have different planting densities; greater densities will encourage more sedimentation by slowing the flow of water. Different grasses are also more effective on different slope elevations, determining the velocity of the water it can retain (Low Impact Developments Centre, n.d.). Testing various grasses under the same conditions may show whether particular grasses perform more effectively at reducing runoff in standard vegetated surfaces.

### 2.3.4- Review of Design Criteria for Flow and Pollution Control

Swales can be used in a variety of environments from being incorporated into new urban developments to retrofitting into existing sites. These devices are less suitable for private gardens due to the area of land required especially in dense developments with little existing landscaping (Wilson et al. 2004:191). One of the key aspects of the design of swales and filter strips is that flows should not exceed 0.15m/s and that the length should be at least 60m to create a residence time of at least 9 minutes (Escarameia et al. 2006:6). This has been shown by numerous studies such as Yu et al. (2001) who studied two swales in Taiwan and Virginia; and found that poor performance in regard to removal of TSS was linked to length of the device. It is also important to note that performance is also dictated by the volume of received water and that even a swale of significant length may display poor performance with excessive runoff volumes. Slower flows are needed in swales to allow the settling of pollutants from runoff as it passes through, therefore they cannot generally be placed on steep slopes due its effect of increasing the velocity of received runoff (Yu et al. 2005) unless they run parallel with the contours of the land. However, even a slight incline is preferable as a flat surface is not a suitable gradient to achieve significant flow and may lead to swales becoming waterlogged and creating standing water. This can affect the overall performance of the swale (Escarameia et al. 2006:16; Latin and Barrett 2005:6), although this can be addressed by adding under drains, such as those shown in Figure 2.4. Such a design is particularly useful in residential areas as it means swales are prevented from becoming boggy in wetter weather (Wood-Ballard et al. 2007:254). More gradual slopes also produced better removal of suspended solids; however it appears to plateau at 75m regardless of the slope, showing that the majority of solids that can be deposited would have been so by this distance. The presence of check dams also increase the efficiency of removing sediments (Yu et al. 2001:170-171). A summary of the design specifications of different vegetated surfaces is shown in Table 2.6.

***Table 2.6****: Summary of the Design Characteristics of Swales, Grassed Channels and Grassed Filter Strip*

(Source: Escaramia et al 2006: 8)

### 2.3.5 - Recommended Grasses

Grasses planted into vegetated surfaces need to have dense surface cover and root structures to resist the flow of water and its erosive force (Wood-Ballard et al. 2007:261). Dense cover also helps reduce flow and the residence time of water in the swale, increasing its performance regarding filtering out suspended solids. Grasses also need to be tolerant of wet and dry conditions and increased levels of heavy metals, whilst presenting an aesthetically pleasing growth to the local environment. Commonly recommended grasses are perennial ryegrasses (*Lolium perenne)* and fescues (Wilson et al. 2004:206; Escarameia et al. 2006:8). Sports Turf Research Institute (STRI – 2007: D Lawson per. comm.) also highlighted Browntop Bent (*Agrostis capillaris syn.tenuis)*, Creeping Bent (*Agrostis stolonifera)* and Velvet Bent (*Agrostis canina)* as being suitable for lawns and landscaping and their high densities could also be beneficial in the performance of vegetated surfaces.

### 2.3.6 - Characteristics of Grass Species Possibly Suitable for Vegetated SUDS

Choosing a suitable grass for a device such as a swale requires a decision based upon its potential to reduce runoff, accumulate pollutants and survive in the environment in which it is going to be placed. Firstly different grasses will have different heavy metal pollutant removal potential meaning consideration is needed to pick suitable grass species for a particular environment. With the SUDS triangle (Figure 2.1) amenity is an issue since grasses need to be attractive as well as functional. Other important factors include tolerance to disease, winter hardiness, blade density and persistence which all have an affect on whether a vegetated surface will be established and become an effective drainage system (Van Huylenbroeck et al. 1999:267). However, grass species will not necessarily have all these favourable characteristics therefore compromises must be made and suitable mixtures recommended.

As mentioned in section 2.3.5, *L. perenne* and fescues are recommended by CIRA for use in vegetated surfaces, with STRI (2007: D Lawson per. comm.) suggesting that different types of Bents and other species such as smooth stalked meadow grass (*Poa pratensis)* are used in landscaping and could therefore possibly be incorporated into vegetated surfaces. These grasses are native to Europe and some have been used in other studies of heavy metal uptake or land reclamation (Civeira and Lavado, 2008; Santibáñez et al. 2008; Evanylo et al. 2005). However grass species such as the Bents have rarely been researched in regard to heavy metal uptake. Perennial ryegrass is a fine leaved grass that is used in most turf produced in the UK. It is a species of grass that is relatively tolerant to drought and salts, displaying a good response to fertilizers (Turfgrass Growers Association, n.d.). The ability to be tolerant to droughts could be useful in the summer months when SUDS systems may not receive much runoff. Also the tolerance to salts could be an advantage with runoff likely to include the de-icing salts (Patel 2005). *L. perenne* has also been used in a large number of studies investigating affects of heavy metals and uptake for contaminated land reclamation. Evanylo et al. (2005) used *L. perenne* in a study involving a contaminated coal mine site. Sixteen species of grass were used in a ten year study to investigate how grasses survive, uptake nutrients and heavy metals over a prolonged period. A similar, shorter study was conducted by Santibáñez et al. (2008) on a copper mining site using *L. perenne* to phytostabilize the area. Cu and Zn were noted to accumulate in the plant tissue; however, these were not at levels considered to be phytotoxic to the plant and within tolerable levels for animals leading to the consensus that *L. perenne* would be suitable for phytostabilization. The ability to accumulate heavy metals would be advantageous for removing heavy metals from SUDS devices and therefore a species that is regularly included in land reclamation has potential for improving the heavy metal retention performance of a swale. *L. perenne* also has been shown to grow well in contaminated soils, for particular areas contaminated by hydrocarbons. Whilst the hydrocarbons affected the development and growth of the grass, it was shown that a grass that had established itself before the addition of hydrocarbons coped much better (Kechavarzi et al. 2007). Studies have also replicated degraded urban soil in plant trays to determine how *L. perenne* accumulated nutrients and heavy metals. There was no recorded statistical difference in the heavy metal concentrations between different treatments though there was a large increase in N causing 40% higher biomass production which would allow potentially higher accumulation of heavy metals in the shoots (Civeira and Lavado, 2008; Sun and Davis, 2007:1608).

Tall fescue (*Festuca arundinacea)* has also been used to study heavy metal uptake, for example Civeira and Lavado (2007) used this species in their urban degraded soil study noting that it could survive as well as perennial ryegrass in degraded urban soils. *F. arundinacea* was also one of the sixteen grass species used by Evanylo et al. (2005) in a ten year study which found *F. arundinacea* was one of four grasses that showed greatest persistence and biomass production, factors that might help accumulation of pollutants (Sun and Davis, 2007:1608). It is also drought and moisture tolerant both of which are important if a sward is to survive all year round. The study also showed that although high levels of Cd, Cu, Ni and Zn were in the soil, the levels in the grasses were well within critical concentrations which would resulting in toxic conditions detrimental to growth (Hopkins and Hüner, 2008:68).

Strong creeping red fescue (*Festuca rubra)* is a slender type of grass that produces underground stems known as rhizomes which help repair any physical damage that may occur. This is a grass that can be cut very close to the ground and has a certain tolerance to salt (Turfgrass Growers Association, n.d.). It is also a low maintenance turf grass that is tolerant of soils with little moisture (Zaurov et al. 2001:1981). Being a low maintenance species is an advantage for use in swales, from a cost perspective, as it reduces the need for maintenance required to repair the effects of wear in comparison to other grasses. Elias (1982) showed the further resilience of this grass when comparing the performance of various grasses on contaminated land. It showed that in soil with a low phosphorous level, similar to reclaimed land, *F. rubra* performed well with growth being fairly unrestricted compared to types of Bent grasses. *P. pratensis* is similar to strong creeping red fescue (*Festuca rubra)* as it also has rhizomes as well as stoloniferous roots that help it recover from drought and physical damage (DLF Trifolium n.d.). This is an advantageous characteristic for a grass that is likely to experience large amounts of wear due to runoff and human activity.

The Bents (*Agrostis canina, Agrostis stolonifera and Agrostis capillaris syn.tenuis*) have been the focus of little research relating to heavy metal uptake or tolerance. However, Pérez-de-Mora et al. (2006) studied how trace elements were removed from the soil using several species including Creeping Bent (*A. stolonifera)*, noting that all the species recorded a decline in trace elements over time. Elias (1982) studied Browntop Bent (A. *capillaris syn.tenuis)* and found that there was restricted growth with low phosphorus levels. Bent grasses are generally used for turf on golf courses because of their aesthetic nature, producing an attractive, dense mat of grass. This makes Bent grasses particularly useful for addressing the amenity aspects vegetated SUDS (BSM Catalogue, n.d.). Promisingly, Bent grasses are compact, having a very high shoot density that is also likely to be useful in slowing water down and promoting sedimentation of suspended solids. They also possess stoloniferous roots that would develop on the surface and possibly increase the accumulation of pollutants from settled sediments. Bent grasses prefer moist to wet soil conditions which are ideal for a vegetated SUDS (DLF Trifolium n.d.).

Some of the key characteristics of the grasses discussed above are highlighted in Table 2.7. Characteristics such as establishment and growth rates are critical in vegetative devices to allow grasses to grow and develop into a surface that can perform as designed and fulfil its potential to remove pollutants and reduce runoff. Wilson et al. (2004:187+198) illustrated in Dundee that a swale with incomplete and unsuitable vegetated cover produced only a 1.2% reduction in runoff as opposed to 52% for a fully developed swale, underlining the importance of the grass in becoming established and growing effectively in order to have an impact on reducing runoff. The ability to recover from wear is also advantageous for swales. The characteristics in Table 2.7 are important to consider as well as their performance in removing pollutants and reducing flows when recommending potential suitable grasses. Other characteristics need to be considered with regard to how a grass reacts to wet conditions, saturated soils and periodic inundation especially considering these are the conditions that the grasses are most likely to be subjected to.

| ***Table 2.7**: Species Characteristics* | | | | | |
|---|---|---|---|---|---|
| | | Highways Agency, 2006 | | | |
| Species | Latin Name | Speed of Establishment (5=best) | Salt Tolerance | Growth Rate (5=lowest rate) | Recovery (5=best) |
| Browntop Bent | *Agrostis capillaris syn.tenuis* | 2 | Susceptible | 3-4 | 2-3 |
| Creeping Bent | *Agrostis stolonifera* | 2 | Moderate Susceptibility | 3-4 | 2-3 |
| Velvet Bent | *Agrostis canina* | 2 | - | 3-4 | 2-3 |
| Perennial Ryegrass | *Lolium perenne* | 5 | Moderate Tolerance | 1-2 | 5 |
| Strong Creeping Red Fescue | *Festuca rubra* | 4 | Moderate Susceptibility | 1-2 | 3 |
| Smooth Stalked Meadow Grass | *Poa pratensis* | 1 | Susceptible | 2-4 | 3-4 |
| Tall Fescue | *Festuca arundinacea* | - | Moderate Tolerance | - | - |

The grasses mentioned in this section offer a range of characteristics which could make them suitable for application in vegetated SUDS. Whilst some of the grass species have already been studied showing some promise in regard to heavy metal removal or tolerance, this study will compare previously tested species with those that have not yet been investigated.

## 2.5 - Urban Pollutants

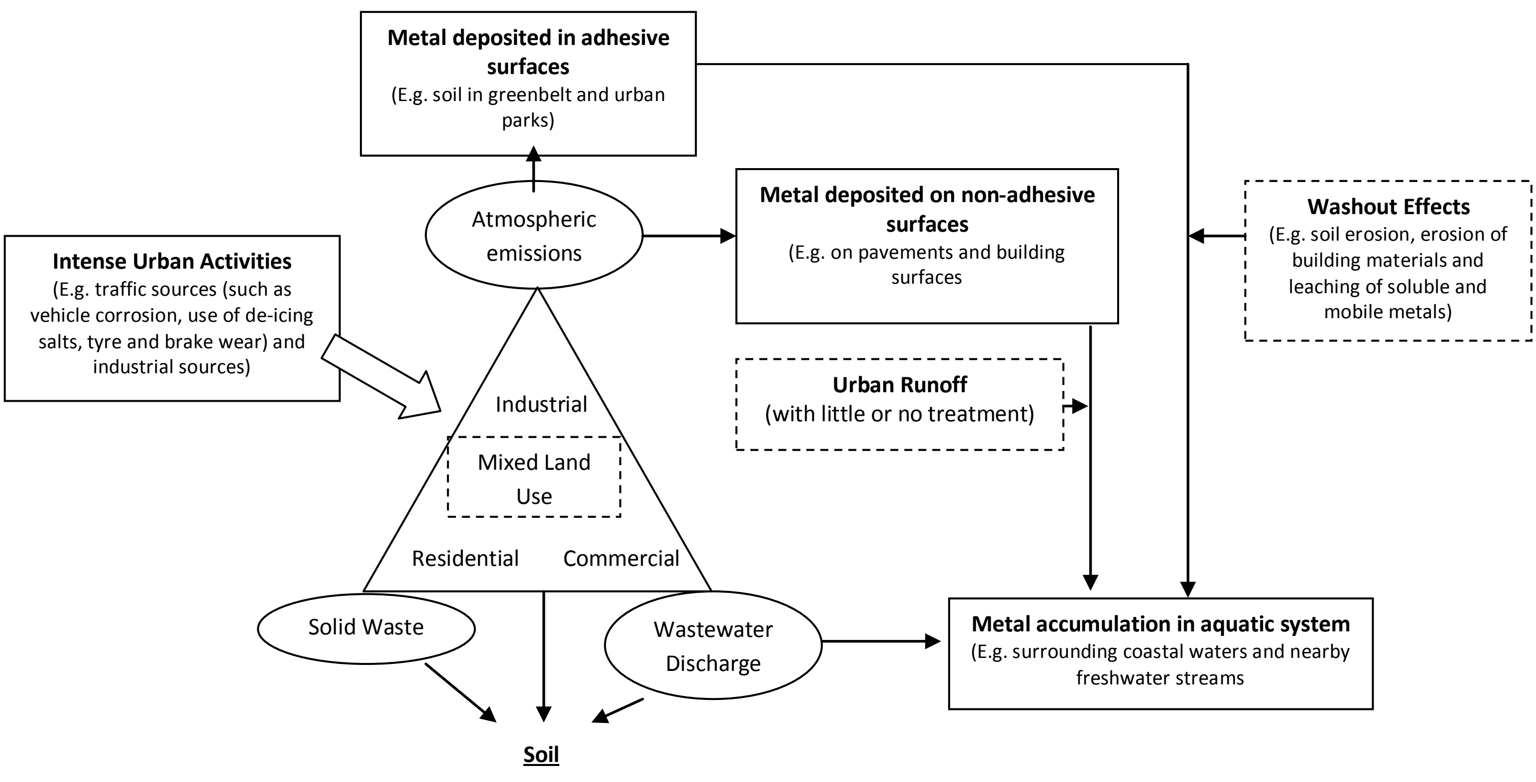
As well as understanding the design of swales and their performance regarding improving quality and reducing the quantity of runoff, it is important to understand the type and source of pollutants in an urban environment in order to investigate how a drainage system would remove such pollutants. In urban areas, land surfaces can be covered with tarmac roads and other impermeable surfaces, offering a surface for pollution to build up on. Dense areas of urbanisation become sources of concentrated pollutants which can lead to negative affects on local aquatic and soil systems (Escarameia et al. 2006). Sources of urban pollutants are detailed by Escarameia et al. (2006:9) and are listed below:

- Fuel combustion
- Vehicle corrosion
- Safety fences and road sign corrosion
- Tyre and brake wear
- Pavement and building wear
- Use of de-icing salts and other products
- Atmospheric fallout

Figure 2.5 shows a summary of these sources along with the processes regarding the transportation of pollutants to aquatic systems in an urban environment.

***Figure 2.5:*** *The processes and transport of metals in urban settings*

(Adapted: Wong et al. 2006:5; Escarameia et al. 2006:9)



### 2.5.1 – Type of Pollutants

Urban sediments are a major source of pollutants, with the majority of the metals and organic materials associated with pollution detailed in this section being capable of absorbing particles and transporting a pollutant as surface water runoff (Escarameia et al. 2006:9). CIRIA Report 142 (1994), which is summarised by Patel (2005), indicates that vehicles are instrumental in the build up of pollutants including, zinc, cadmium, iron, chromium, copper and aluminium. This is often due to corrosion of metals from tyre and brake wear and from other surfaces such as signs, roofs and safety fences (Patel, 2005:137). Particulates are also introduced into the atmosphere from industry, traffic and buildings (See Figure 2.5) where fuels are burnt to produce energy, resulting in dust and fumes polluting the air. Particles larger than 10μm are deposited by the influence of gravity onto nearby surfaces such as roads and pavements (Maynard, 2001). Charlesworth et al. (2003) also showed that former industrial activity in Birmingham had an impact on the concentration of pollutants in street dust with higher concentrations of Cd, Cu and Zn found in the north-west of the city where brass and coin making industries were prevalent. These concentrations lowered dramatically in the more residential parts of Birmingham. Other pollutants are generated from human activities such as the use of fertilizers and herbicides on a front lawn and improper disposal of waste products such as cleaning products and oils. Cuttings from gardens and green areas can also provide organic matter and litter. This can all be mobilised and picked up by surface runoff (Escarameia et al. 2006:9). However, the difficulty in managing sources of pollution is that they have no fixed point and they are highly episodic (Ellis and Mitchell, 2006:19). As well as water courses, soil could also develop high concentrations of heavy metals which could result in toxic affects to both humans and animals.

Deposition of dusts and fine material that become part of the sediment matrix in urban areas are not from one location but rather originate from various sources making it difficult to regulate and protect against (Wong et al. 2006:5). At the beginning of a rainfall event the layers of dust and pollutants are washed off surfaces such as roads and pavements and mobilised; travelling into local water courses or drainage systems. This is known as first flush and studies on a variety of land uses in Florida have shown that 80-

95% of total annual loading of most stormwater pollutants is as a result of this (Martin et al. 2000:42-43; Sansalone and Cristina, 2004:1310). It becomes difficult with traditional drainage devices to deal with the adverse affects that these pollutants have on water quality (Wong et al. 2006:4-6). One way to do this would be to remove them at source minimising the disturbance they can have or convey them to an area where they can be safely and efficiently removed, something that SUDS aim to achieve.

### 2.5.2 - Key Pollutant Determinants

Escarameia et al. (2006:10) broke key pollutant determinates into the 5 following categories:

1- Sediment – Total Suspended Sediment (TSS)
2- Heavy Metals – Copper(Cu), Zinc (Zn), Aluminium(Al), Cadmium (Cd), Lead (Pb), Nickel (Ni), Chromium (Cr)
3- De-icing Salts – (Ha+Cl)
4- Hydrocarbons – PAH and 16 specific PAHs (such as Benzo(b)fluoranthene)
5- Herbicides

The present study focussed on the first two categories as the majority of other investigations shown by Escarameia et al. (2006) (See Table 2.4) on swales and filter strips examined these pollutants and they are therefore comparable. The most studied metals are Cd, Cu, Ni, Pb and Zn, which are all used in commercial products such as tyres, brakes and building materials such as metal roofing (Wong et al. 2006:3). Cu and Zn are naturally occurring heavy metals that are essential for biological processes in plants (Hopkins and Hüner, 2008:66). Cd and Pb are rarer and are found in much smaller concentrations in the soil. Pb in particular also has a low solubility and therefore limited uptake by grass and as such remains near the surface soil horizon (Davies, 1989). These metals have been identified as stormwater pollutants by the Water Framework Directive and are noted as frequently found in urban stormwater, thus a large number of studies have investigated them with respect to drainage issues (Eriksson et al. 2007:44, 47). Barrett et al. (1998) examined highway runoff in Austin, Texas by sampling water quality determinants on several different streets in order to help evaluate swale performance in treating highway runoff. Analysis was conducted to determine the concentrations of six heavy metals (iron, lead, cadmium, nickel, zinc and copper) and the total suspend solid (TSS) removal. The study showed that swales are effective at removal of TSS as well as reducing concentrations of Zn and Fe by 79%; with these metals being up-taken by grass or held in the soil matrix. Studies on the sources of pollutants as well as grass uptake focus on similar heavy metals. Kalis et al. (2007:336) investigated Cd, Cu, Pb, Ni and Zn to determine the process behind the uptake of heavy metals by *Lolium Perenne,* providing a stepped process of how metals are taken from the soil and transported to the shoots. This was done using a pot based study with analysis being conducted on the various plant components involved in heavy metal accumulation (soil, roots and shoots). The chosen heavy metals are also mentioned in relation to analysis and study of street dust and urban runoff. Charlesworth et al. (2003) was one such study that investigated these heavy metals to compare their distribution in street dust in Birmingham and Coventry finding that heavy metals in deposited street dust were influenced both by traffic conditions and where there had been previous industrial activity. Sediments such as street dust would be washed into SUDS such as swales and therefore it is important to understand the potential input of pollutants into these drainage systems. Table 2.8 summarises a number of studies that have been conducted on street dust and the pollutants on which they focussed.

***Table 2.8***: *A Summary of Street Dust Studies Involving Heavy Metals*

| | | | **Concentrations (mg/kg)** | | | | |
|---|---|---|---|---|---|---|---|
| **Author** | **Subject** | | **Cd** | **Cu** | **Ni** | **Pb** | **Zn** |
| Zander (2005) | Road sediment characterisation in Hamilton (New Zealand) | | - | 181-212 | - | 251-334 | 1073-2080 |
| Charlesworth et al (2003) | Conc. & distribution of street dust | B'ham (UK) | :1.62 | 466.9 | 41.1 | 48.0 | - |
| | | Cov(UK) | 0.9 | 226.4 | 129.7 | 47.1 | - |
| De Miguel et al. (2007) | Risk analysis of street dust in Madrid (Spain) | | 0.19 | 20 | - | 38 | 78 |
| Elik (2003) | Street dust analysis in Sivas, (Turkey) | | 2.6 | 84 | 68 | 197 | 208 |
| Ferreira-Baptista & De Miguel (2005) | Risk analyse of street dust in Luanda (Angola) | | 1.1 | 42 | 10 | 351 | 317 |
| Brown & Peake (2006) | Study of heavy metal sources in urban areas –street dust in Dunedin (New Zealand) | | - | 129 | - | 289 | 528 µg/g |
| Wilson et al (2003) | Performance of pervious pavement with street dust | | 0.9 | 170 | - | 130 | 630 |

To control both potential pollutants and volume of urban runoff, a drainage system needs to be well designed and easily installed in an urban area. SUDS are an alternative to traditional drainage systems offering a naturally inspired approach. However, as well as having many strengths, this chapter has highlighted that some SUDS devices, in particular vegetative ones such as swales, require further research into their performance and the selection of grass species that are used which could provide information leading to an overall improvement in regard to their retention of heavy metals and runoff.

## 2.6 - Aims & Objectives

Several species of grass have been identified as suitable for use in vegetated surfaces. However, there is little quantitative evidence that offers a comparison between the performance of the different species in hydraulic retention and their ability to uptake and retain pollutants, particularly in urban conditions. This study aims to determine whether one particular grass species shows more potential than another in this regard.

The specific aim of this study is to recommend suitable grasses for use in vegetative SUDS devices. This will be achieved with the following objectives:

- To determine the distribution of heavy metals in different grass species
- To determine the hydraulic retention capabilities of the grass species

The following chapter outlines the method that was used to achieve the research aim and objectives.

# 3.0 Method

This chapter discusses the trials that were set up to address the objectives detailed in the previous chapter. This involved pollutant retention trials to measure the pollutant retention capabilities of the selected grasses discussed in this chapter, determining whether pollutants are accumulated or remain in the compost. It also involved hydraulic retention trials to determine whether particular species are more suitable at slowing runoff and encouraging infiltration. The first section discusses the rationale behind the grass species that were selected for both trials.

## 3.1 Selection of Grass Species

There have been recommendations of grass types for use in swales and filter strips by organisations such as CIRIA and the Highways Agency (Wilson et al. 2004:206; Highways Agency, 2006). Other studies recommended similar grasses based on other characteristics such as aesthetics (DLF Trifolium, n.d.). As well as these grasses being recommended for  swales and filter strips they are recommend for Grassblock, which is a grass and concrete matrix designed for car parks and embankments to be functional for drainage but also aesthetically pleasing (Grasscrete n.d.). The recommendation of other studies which, refer to grasses such as *L. Perenne*, illustrate that this is a group of plants that are thought to be suitable for vegetated surfaces. Based on this, the grass species were chosen and are shown in Table 3.1. These species of grass were chosen because they are native to Europe, and have been used previously in tests examining site reclamation of heavy metals. Grasses such as the Bent grasses are generally used for sports turf such as golfing greens; these were included due to the lack of data on how they respond to street dust and heavy metal pollution (Evanylo et al. 2005; Santibáñez et al. 2007; Begonia et al. 2005; Bidar et al. 2007). However, The Highways Agency (2006) does provide details on grass species including the Bents, regarding factors such their establishment rates and salt tolerance (See Table 2.7). All the seeds for these species have been supplied by Dr David Lawson of STRI with recommended sowing densities advised by STRI.

| ***Table 3.1:*** *Selected Grass Species Characteristics* | | |
|---|---|---|
| **Species** | **Latin Name** | **Recommend Sowing Density** |
| Perennial Ryegrass | (*Lolium perenne L.)* | 35g/m$^2$ |
| Tall Fescue | (*Festuca arundinacea)* | 35g/m$^2$ |
| Strong Creeping Red Fescue) | (*Festuca rubra)* | 35g/m$^2$ |
| Smooth Stalked Meadow Grass | (*Poa pratensis)* | 35g/m$^2$ |
| Browntop Bent | (*Agrostis capillaris syn.tenuis)* | 20g/m$^2$ |
| Creeping Bent | (*Agrostis stolonifera)* | 20g/m$^2$ |
| Velvet Bent | (*Agrostis canina)* | 20g/m$^2$ |

## 3.2 - Simulating Urban Pollutants

It was decided to collect street dust rather than using synthetic approximations. The material was readily available from the mechanical street sweepers operated by Coventry City Council. This avoided the need to collect the street dust at the road side, therefore removing any safety issues. This method of collecting street dust would allow a large amount to be collected at once in a relatively short period of time. Also because it was being collected across the whole city centre it would be more homogenous than point sampling and therefore reduce anomalies, producing a representative sample. Coventry street dust should also have similar characteristics to material from urban runoff that would be washed into a swale or filter strip. This would allow it to behave in a realistic fashion as opposed to synthetic liquid approximations of urban pollutants used in trials such as Yu et al. (2001) that might allow the heavy metals to be more easily accumulated in plants. Heavy metals in street dust are also linked to particulates meaning they are generally not available to grasses (Zander, 2005). Using synthetic approximations therefore could produce misleading and unrealistic results.

### 3.2.1 - Processing the Street Dust

The street dust was collected from Tom Whites Disposal Yard in October 2008, where the mechanical street sweepers that service the CV1 area of Coventry deposit their load. The CV1 area includes all of the city centre area within the ring road. This area mainly comprises of retail areas and some residential sites. Material was collected after a three day dry period to ensure that street dust had accumulated. It was sieved through a 2mm sieve in order to remove the larger components such as leaf litter and from a safety point of view, hazardous objects such as glass and damaged batteries.

The process of homogenising the street dust is shown in Figure 3.1. Once sieved, the material was oven dried at 40$^{o}$C for 48 hours before being weighed into equal quantities and placed in a ball mill without the grinding balls (See Figure 3.2). This was then placed on rollers and turned for 48hrs, allowing the dust to grind and mix itself. The reason for this method of grinding was to retain the physical characteristics of the street dust and yet still homogenise it (Charlesworth et al. 2003). If the ball mill was used properly, the resulting processed material would not represent or behave like street dust. Each batch was then re-sieved through a 2mm mesh sieve to remove any remaining larger material and stored in re-sealable polythene bags.

***Figure 3.1:*** *A summary of the street dust homogenisation process*

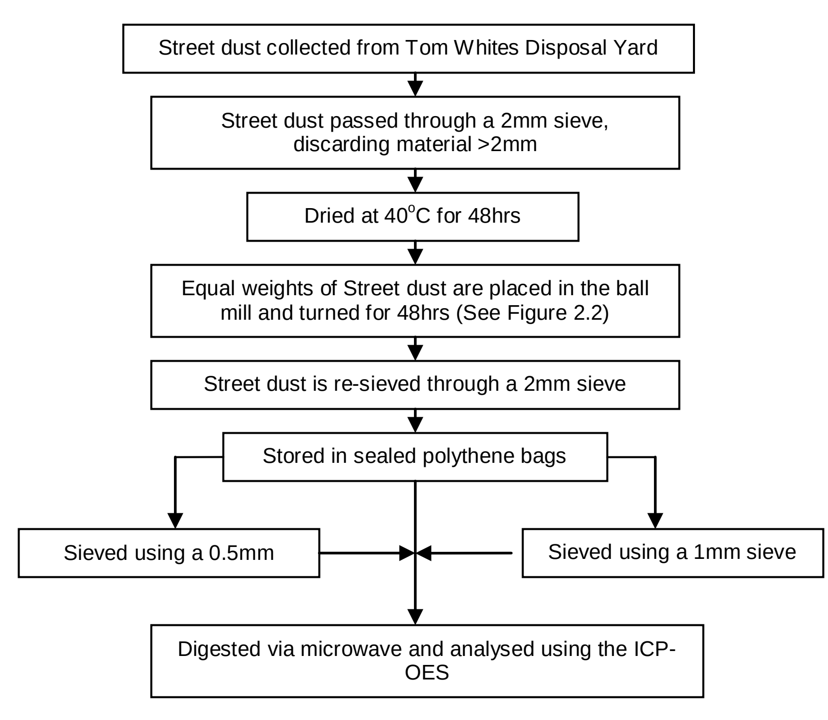
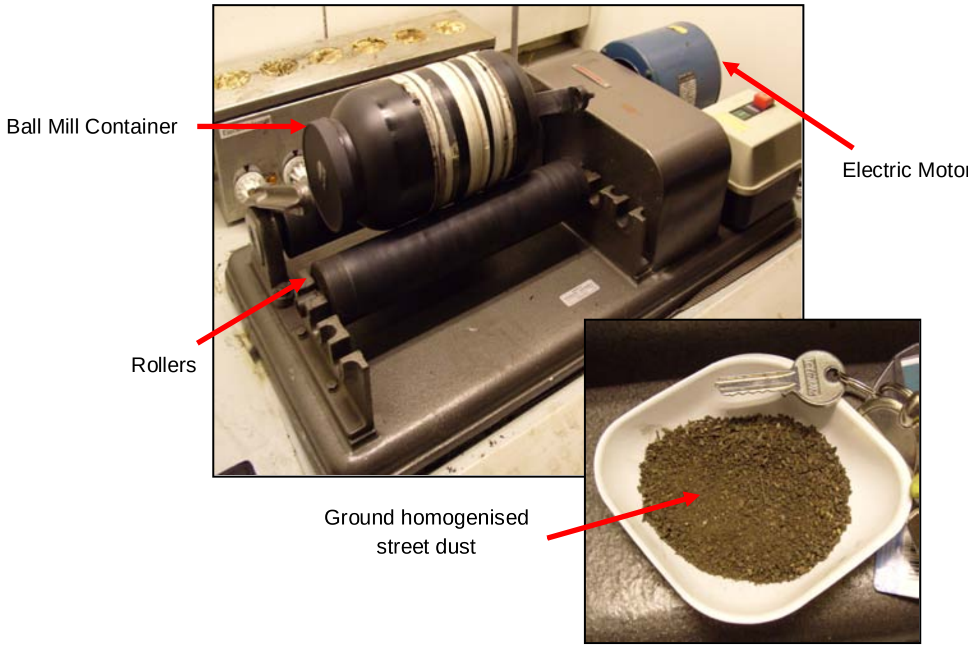


***Figure 3.2**: Ball Mill*




One concern was that milled street dust would have a larger range of concentrations of heavy metals depending on the size at which it was sieved. In order for the street dust to be useful in experimental trials a small range of possible concentrations would be needed so that estimates could be made of the volume of heavy metals being adding to a sample. To evaluate the homogenisation process the milled street dust was sieved using 2mm, 1mm and 0.5mm mesh sieves. Eight samples were taken from material that had passed through each of the sieves and digested using a microwave digestion system (see section 3.5.2). These samples were then analysed for cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni) and zinc (Zn) using an Inductive Coupled Plasma Spectrometer Optical/Atomic Emission Spectrometer (ICP-O/AES). The standard deviation of these results is displayed in Table 3.2 and shows that the 2mm sieved street dust had the smallest overall standard deviations and therefore the most consistent results out of the three street dust particle sizes, this size was therefore used in the subsequent experiments.

***Table 3.2:** Standard Deviation of Street Dust Digests*

| Sample Size | Concentration (mg/kg) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Cd | | Cu | | Ni | | Pb | | Zn | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| 2mm | 1.23 | 0.26 | 268.66 | 63.33 | 19.42 | 1.41 | 86.94 | 14.85 | 438.26 | 38.05 |
| 1mm | 2.14 | 2.65 | 364.17 | 355.56 | 19.03 | 2.93 | 68.40 | 7.57 | 459.76 | 174.86 |
| 0.5mm | 1.30 | 0.98 | 222.18 | 102.03 | 17.55 | 3.58 | 68.11 | 15.55 | 317.22 | 30.53 |

Thirty two <2mm street dust samples were analysed to provide information on the ranges of concentrations for each heavy metal in the street dust. This provided an estimation of the heavy metal concentrations which would be applied to the experimental pots, determining where the majority of the pollutants were distributed. The information in Table 3.2 also shows that Cu and Zn concentrations appear to be highly variable and that this would need to be taken into consideration when interpreting results.

To be representative of urban pollutants, street dust would need to be added to the pots in the pollution retention trial in quantities that would be found in urban environments and compared to other similar studies. Curtis (2002) studied the streets of Montgomery County, US finding that in 2000, 2093.73 tons of street dust was swept off 3779.31 miles of curb. This works out to 3.46g/curbs-metre of street dust. Pitt et al. (2004) stated that the usual amount of street dust in urban areas is between 1.5 – 2.5g/m$^2$, with a dirty street being considered to have an amount of 10.5-12.6g/m$^2$ and clean streets having an amount of 1.7 – 2.6g/m$^2$. CIRIA Report 142 reported that the street dust deposition rate on roads with >5000 vehicles was 2500kg/ha/yr. Assuming there was no rain for 2 months the report detailed that over an area of 12.5m$^2$ there would be a build up of 0.52kg street dust (Wilson et al. 2003:54). The amount of street dust that was applied is discussed in the following section.

### 3.2.2 - Application of Street Dust

Using the figures in the previous section for the build up of street dust over a 12.5m$^2$ area, the amount that would settle on the area of one pot (0.09503m$^2$) can be calculated. This calculation estimates that 3.952g of street dust would be deposited over a 2 month dry period over the area of one pot (Wilson et al. 2003:54). However, swales would not just have to deal with what was deposited on them but what was washed into them from a larger area. Therefore for the purpose of this study, the build up of dust on an area of 1m$^2$ was used in order to represent the area from which street dust would accumulate before being washed into a vegetated system. According to the CIRIA Report 142, 1m$^2$ would have deposited 41.6g/m$^2$ of street dust over a 2 month dry period (Wilson et al. 2003:54). This would mean that 20.8g of street dust would be deposited over 1 month with 10.4 g/m$^2$ over 2 weeks and 5.2 g/m$^2$ over 1 week.

Values of 40g, 20g, 10g and 5g were chosen to represent the street dust that would be deposited on a surface and transported into the swale or filter strip, simplifying the above values for easier and quicker application. An area of $1m^2$ was chosen as it represented approximately double that of Wilson et al.'s (2003) trial surface. The porous paving used by Wilson et al (2003:53) had street dust applied based on the application of pollutants to a private drive and scaled down to the size of trial section which was $0.585m^2$ and had 21g of street dust applied. By using $1m^2$ to represent the area for street dust deposition, a high loading could be tested on the grass pots which would provide a clear response from the grasses yet was still a realistic amount that the grasses could be subjected to in the real environment

## 3.3 - Pollutant Retention Trials

The pollutant retention experiment consisted of a series of pot trials that were designed to test the distribution of heavy metals when varying amounts of homogenised urban pollutants (street dust) were applied directly to the soil. By using different species of grass in these pot trials, comparisons were made to determine whether a particular grass was more effective at taking up pollutants or whether they all reacted in a similar way. The trials were conducted at Coventry University, UK in a greenhouse situated at $52^{o}24^{'}$ N $1^{o}30^{'}$W (Google Earth 2008) and commenced in January 2009. The greenhouse provided an environment that had a regulated temperature of $25^{o}$C +/- $5^{o}$C.

The grasses were sown at the densities shown in Table 3.1. These are densities recommended by the STRI for these particular species of grass to be sown at to achieve a healthy grass cover (D Lawson per. Comm.). Although variable density of sowing could have a large impact on the effectiveness of a swale it was decided that by using a standard sowing density it would maintain a real life representation of swale landscaping practice and performance with different grasses. Comparability is an important issue with the Bents being sown at a different density to the other four species. This meant that any comparisons needed to take into account these different sowing densities. Seeds were sown in a 13F pot (11cm diameter) and filled with 400g John Innes Seed Compost. These pots were used because that would allow a large enough amount of grass to be grown and sampled.

### 3.3.1: Experimental Design

Two hundred filled pots were arranged into eight blocks of twenty five. Each species of grass was sown into one block with the remaining block used as a control with no grass. Each species received four different concentrations of street dust (40g, 20g, 10g and 5g - See Section 3.2.2). This resulted in each concentration of street dust having 5 replicates with an additional 5 control pots per block. Each block of pots was organised into a Latin Square, designed to take into consideration edge factors such as temperature, air movement and light intensity. Table 3.3 shows the Latin square setup that was used for each set of species or control.

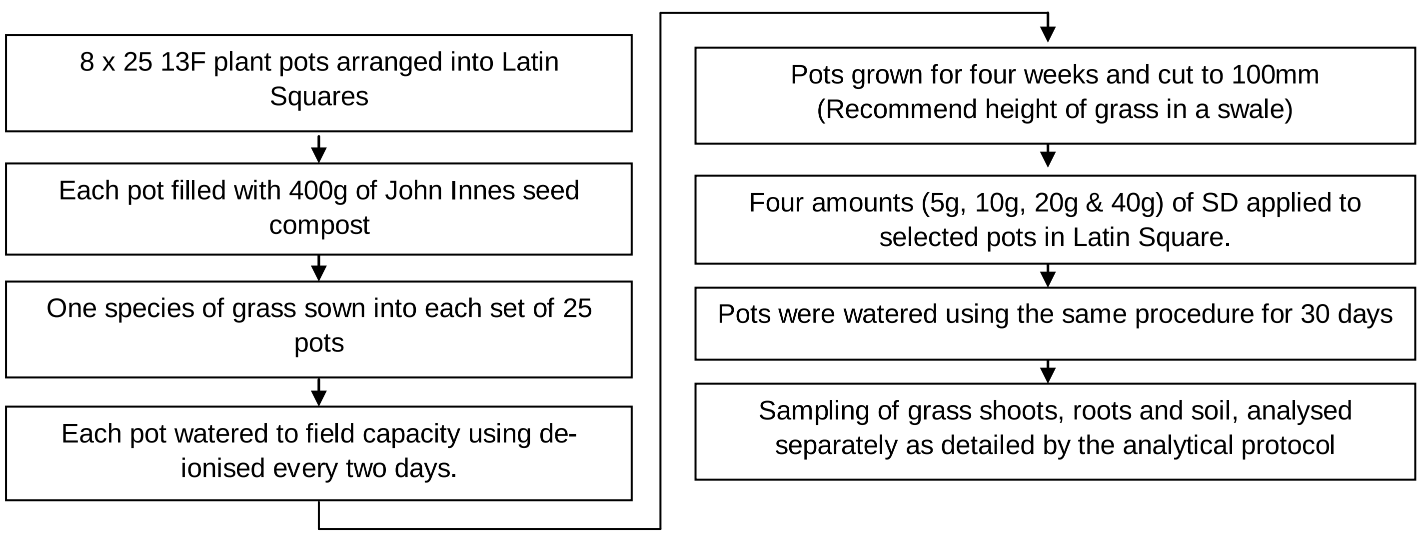
***Table 3.3:*** *Latin Square Arrangement of Street Dust Concentration*

| | | | | |
|---|---|---|---|---|
| Pot 1 – Control | Pot 2 - 5g | Pot 3 - 10g | Pot 4 - 20g | Pot 5 - 40g |
| Pot 6 - 40g | Pot 7 - Control | Pot 8 - 5g | Pot 9 - 10g | Pot 10 - 20g |
| Pot 11 - 20g | Pot 12 - 40g | Pot 13 – Control | Pot 14 - 5g | Pot 15 - 10g |
| Pot 16 - 10g | Pot 17 - 20g | Pot 18 - 40g | Pot 19 - Control | Pot 20 - 5g |
| Pot 21 - 5g | Pot 22 - 10g | Pot 23 - 20g | Pot 24 - 40g | Pot 25 - Control |

## 3.4 - Growing Procedures

The grass pots were watered with de-ionized water once every two days to field capacity where the soil was saturated and unable to hold more moisture. This was measured by watering the pots until they showed the first visible signs of water appearing under the pot, ensuring that the compost stayed moist as required (John Innes, n.d.). De-ionized water was used as it has fewer impurities that could affect the testing. All the grass species were grown for four weeks to allow the grass to develop. The grass was then cut to the recommended length for swales detailed by Wood-Ballard et al. (2007:253) of 100mm. The various amounts of street dust were then evenly applied to each pot. This was watered into the pots with 98ml of de-ionised water which represented runoff from the 1m$^2$ area that would cause the first flush. This figure was calculated from rainfall collected from a weather station in Tile Hill, Coventry and displayed on the Bablake Weather Station website (Bablake Weather Station, n.d.). Data was taken from the 3 previous years summer months to determine the average amount of rain per rainfall event. After this was applied, the grasses were watered with the same regime as before for a further 30 days before harvest of the various components of the grasses. The whole growing procedure is summarized in Figure 3.3.

***Figure 3.3:*** *A Summary of the Growing Protocol for the Pollution Retention Trials*




## 3.5 - Analysis Protocol

Once the trial was completed, analysis could begin on the various components. This involved determining a method of sampling as well as the process of homogenising the samples and performing the analysis. Certain aspects such as the analysis of samples were similar and often repeated though there was still a need to make sure that representative samples were gathered. The following sections describe the processes and considerations that were made through the whole analytical process.

### 3.5.1 -Harvesting & Collection of Samples

Initially the grass shoots were collected and were cut at the base of the plant above the compost. They were analysed for heavy metals in order to determine heavy metal up take from the compost. After the shoots were cut, their fresh weight was recorded before they were dried at 80$^{o}$C overnight. The dried material was passed through a plant mill in order to grind the shoots down to a fine powder, which was stored in labelled re-sealable polythene bags (Shu et al. 2002:446). This ensured that the samples were in a representative form ready for analysis. After each sample was milled the plant mill was dismantled and thoroughly cleaned using a brush and a finer tipped brush to ensure that all traces of the sample were removed before the process was repeated. This ensured that risk of sample contamination was minimal. Furthermore a vacuum pump situated above the plant mill was used as a health and safety precaution to remove any fine particles that became airborne during the use of the mill. To further minimise the health risks a face mask was always worn while using the plant mill.

To sample the compost a core was taken from the centre of each pot. This enabled an assessment of whether the street dust remained on the surface of the compost or migrated through the compost profile. Cores were obtained from each pot using a cork borer. The cork borer had diameter of 15mm and was 100mm long, allowing each pot to be sampled in an identical way providing a representative sample. The core produced was approximately 6cm long which was divided into 3 segments; Layer A, Layer B and Layer C. Layer A was from the surface to a depth of 2cm, Layer B from 2cm to 4cm and Layer C comprised the remainder of the core. Layer B was sampled to determine whether the street dust was migrating down through the pot so the same depth was sampled for every pot. Layer A was not extensively sampled as it would be considered biased due to the direct application of the street dust. Layer C was also not extensively sampled as it was hypothesised that the street dust might not penetrate that far into the compost profile in quantities that would be distinguishable from that present in plain compost. However, samples for Layer A and C were also collected to determine where the street dust was concentrated although due to the volume of samples only 3 samples were collected from Layer A and C for each species. These were collected from pots treated with 40g street dust as this was likely to produce the clearest results due to the larger volume of pollutants. These samples were dried then ground into a homogenous powder in a pestle and mortar. A pestle and mortar was used because the mechanical mill was not be able to separate the soil and root material as it simply grinds the sample until it fitted through a selected sieve. A pestle and mortar allowed for the gentle disaggregation of the compost and the removal of the larger root systems by hand as well effectively homogenising the sample. Once the samples were ground they were passed through a 2mm mesh sieve, and stored in labelled, re-sealable polythene bags.

Finally the grass roots were collected from the remainder of the compost to determine whether there were any links between the heavy metal concentrations in the compost, roots and grass shoots. The roots were not homogenised using a mill of any kind due to the difficult nature of collecting roots that were not contaminated, with only enough material being collected for analysis. Due to time constraints 15 samples were collected per species, consisting of 3 replicates for each treatment. These roots were picked from the pots before being rinsed under deionised water to wash off any compost. They were then patted dry with a towel before being dried overnight at 50$^{o}$C and weighed.

### 3.5.2 - Digestion of Samples

With concentrations of heavy metals such as cadmium likely to be low in the compost, roots and shoots, accuracy and precision was required (Wild, 1993). Both compost and plant material was digested using acids. Nitric acid is capable of digesting most samples with addition of other components such as hydrochloric acid to complete digestion of tougher samples (Clesceri et al. 1998:3-6). The acid digestions can either be done in boiling tubes sitting on a hot plate or using a microwave assisted oven. Closed microwave-assisted acid digestions have been extensively used for sample digestion and for this reason used in this study (Araújo et al. 2002:2122). Closed microwave is a method of speeding up the time of digestion as well as increasing the number of samples that can be simultaneously digested. The samples requiring digestion were placed into a vessel made of Teflon, which is transparent to microwaves allowing samples to be heated more efficiently, and acid was added. By having closed vessels the pressure can build up leading to a more effective digestion process (Christian, 2003:59). The closed vessel also means less chance of contamination and also uses less acid (Barrett, 2000:13). Due to the microwave system being able to take 40 samples at one time it digested large quantities of both plant and soil samples. Also with the large number of samples analysed, any reduction in the amount of acid would reduce the need for further resources. Microwave digestion was also a suitable method for small sample amounts. With such digestion needing a minimum of 0.2g of material there was no difficulty in obtaining sufficient sample material (Araújo et al. 2002:2122). Methods involving microwave-assisted digestion are also recommended for the analysis of many elements including the five heavy metals that were analysed in this study (Clesceri et al. 1998:3-7).

The digestion process for all the samples was the same. The only variable was the amount of sample to be digested; 2g of compost, 1g of grass shoot and 0.5g of grass root. Less plant material was required as it was less dense, taking up more room in the digestion tubes. The step by step process of digestion is shown in Figure 3.4.

***Figure 3.4:*** *Step by Step Process of Microwave Digesting*

2g of sample placed in digestion tube

↓

Re-weigh weighing boat to determine the total sample weight in digestion tube

↓

2ml hydrochloric acid and 6ml nitric acid added

↓

Add spike solution (2ppm Ni, Zn, Cd, Cu & Pb) to two empty digestion tubes

↓

Carousel placed in microwave using program as follows:

Step 1 – Ramp to 60$^{o}$C (5mins) and hold at 70$^{o}$C (5mins)

Step 2 – Ramp to 90$^{o}$C (5mins) and hold at 100$^{o}$C (5mins)

Step 3 – Ramp to 120$^{o}$C (5mins) and hold at 120$^{o}$C (5mins)

Step 4 – Ramp to 150$^{o}$C (5mins) and hold at 150$^{o}$C (5mins)

Step 5 – Ramp to 180$^{o}$C (5mins) and hold at 180$^{o}$C (15mins)

↓

Tubes removed from carousel and placed in fume cupboard to cool for 10mins

↓

Digestion tubes rinsed with de-ionized water through filter paper into a 25ml volumetric flask. Flasks made up to 25ml with de-ionized water.

The quantity of acid used for the digestion was determined by the amount of liquid absorbed by the dry organic matter and compost. 8ml of acid was judged to be enough to cover the sample so that it could be digested. The acid used was a reverse aqua regia mixture of nitric ($HNO_3$) and hydrochloric acid (HCl) at a ratio 3:1 $HNO_3$: HCl (vol/vol). Nitric acid, when heated is enough to dissolve most metals with HCl being included to dissolve more difficult materials. This is particularly effective at the high temperatures achieved in the Teflon-lined vessels of the microwave system (Harris, 1999:826). With small samples being analysed the amount of acid used was kept at a minimum. The samples were decanted into a 25ml volumetric flask after digestion was complete so that a larger volume of de-ionized water could be used to wash the insides of the digestion tubes clear of digested sample. This ensured that as much of the sample was obtained as possible.

### 3.5.3 Quality Assurance

Spike solutions were also added to two empty digestion tubes for each digest. A spike solution is simply a known concentration of a set of elements that were to be analysed (Clesceri et al. 1998; 1-6). These spikes were processed in the exact same way as a sample and were designed to show the accuracy and recovery of samples with the chosen method. Inaccuracies can then be dealt with by changing aspects of the method. The spike solution as shown in Figure 3.4 contained the same 5 heavy metals to be analysed in the compost and plant material: cadmium, copper, lead, nickel and zinc. The concentrations of these spikes were close to the estimated concentrations of the samples (Clesceri et al. 1998; 1-6). A spike of 2mg/l was used for analytical spikes as concentrations were expected to be relatively low when trial digestions were carried out on the soil and plant cuttings. To ensure reliability, two blanks and two spikes were included with each microwave carousel. Relative standard deviation (RSD) was also calculated to show the spread of data. A suitable RSD would be <20% with spikes of 100%+/- 10% being deemed as showing good laboratory practice, though spikes are acceptable up to 100%+/- 20% (Clesceri et al. 1998; 1-5).

## 3.6 – Other Analysis: Methods of Compost Analysis

Other aspects of the pot trials were also investigated using techniques other than microwave digestion and ICP-OES. With large numbers of sample pots, methods of analysis were needed that could allow determinations to be made about where street dust was distributed within the soil profiles and the factors which might influence how nutrients were taken up by the grasses. Two techniques were chosen; mineral magnetism and pH with the following sections detailing the methods that were used as well as the reasons behind choosing these two techniques.

### 3.6.1 - Mineral Magnetism

Mineral magnetism can be used to characterise various types of sample. This is a fast and non-destructive way of assessing samples for evidence of pollution through a sediment column, allowing large numbers of samples to be analysed economically and not limiting subsequent analysis on a sample (Dearing, 1999:4-5). Magnetism in this study was used to determine whether the street dust had migrated down the profile of the compost by sampling the street dust and original compost to act as indicators of their magnetic susceptibility before collecting samples of compost from selected pot trials and measuring the magnetic susceptibility at different points. Street dust includes deposits from various anthropogenic sources (e.g. cars, metal surfaces etc) and so has a higher susceptibility than the compost, so when plotted for each sample these points show where the street dust migrated in the compost profile.

Samples from the pot trials were collected by separating the cores taken from the pots into 2cm segments. Figure 3.5 shows the methodology behind the mineral magnetism testing. Once testing was completed the magnetic susceptibility was plotted to determine the downward distribution of applied street dust. This allowed a determination of the presence of street dust in the compost profile without having to spend time digesting each layer.

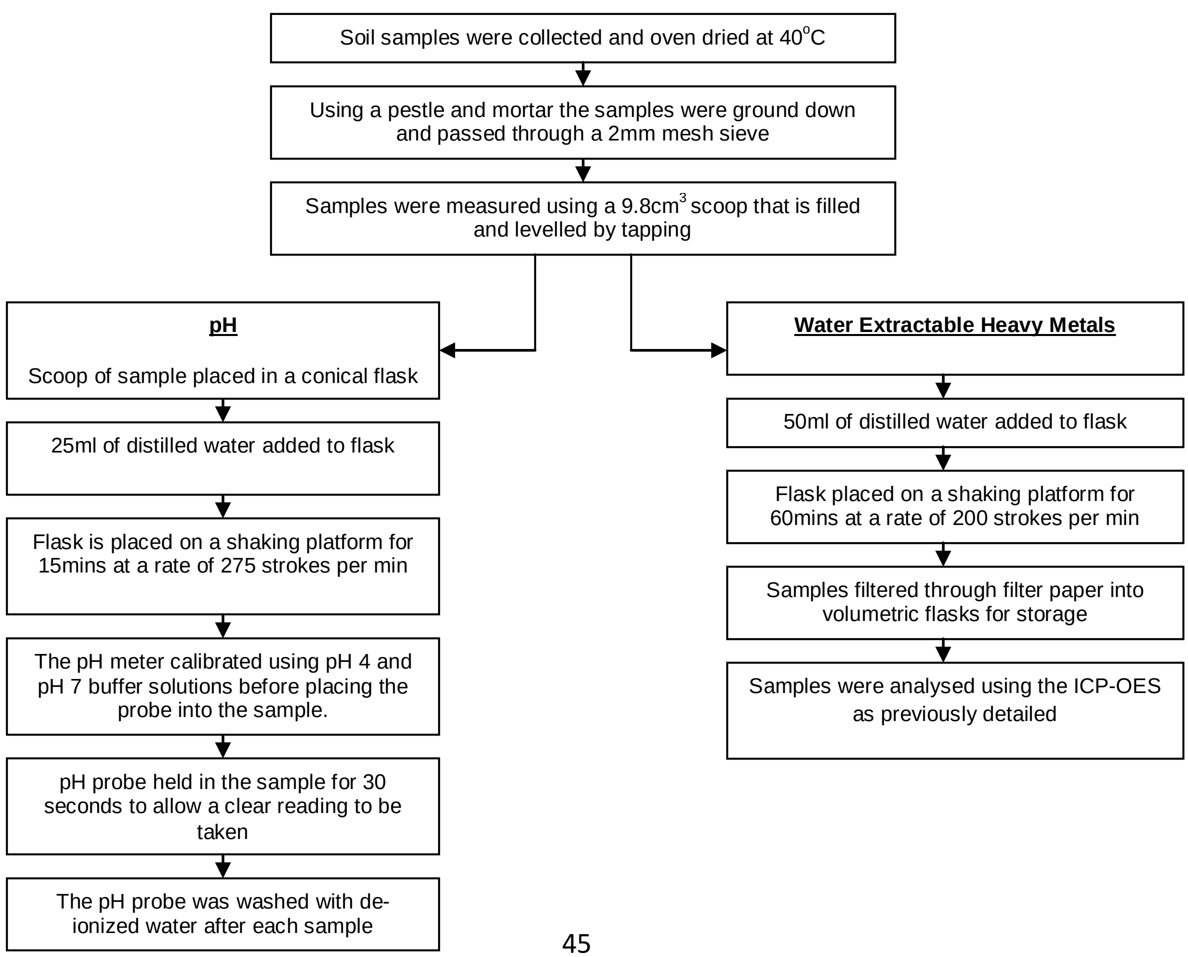
***Figure 3.5**: Mineral magnetism methodology*
(Source: Charlesworth and Lees, 2001:p116)

## 3.6.2 - Compost pH

The pH has been described as a controlling factor in the uptake of heavy metals into the soil (Kalis et al. 2007). Heavy metals such as Cu and Zn show increasing availability with decreasing pH in the soil (Taiz and Zieger, 2006:83), and several greenhouse studies have also shown an increase in the uptake of heavy metals with decreasing pH (Antoniadis et al. 2008:760). Kalis et al. (2007) investigated *Lolium perenne* and the factors influencing the uptake of metals, concluding that there were several factors that were important, such as bioavailability of metals and total metal concentration in the soil, although it was thought that metal absorption to the root surface is pH dependant. Kalis et al. (2007) found that up take of Ni was particularly related to the pH of the soil. Some constituents of street dust are substances such as de-icing salts which are alkaline, therefore street dust could have an affect on the pH of the compost (Patel, 2005). De-ionised water used may also affect the pH as it can be alkaline in comparison with tap water. The presence of rainwater in the natural environment would also alter the pH due to its acidic nature, something that may aid uptake of nutrients by the grasses.

Samples for pH were collected from the top 2cm of the soil cores and oven dried before being ground and passed through a 2mm mesh sieve. A 9.6cm$^2$ scoop was then filled and levelled without tapping, before being transferred to a glass bottle or conical flask; 25ml of de-ionised water was then added to the flask, which was then placed on a shaking platform, secured and shaken for 15mins at a rate of 275 strokes per min. Buffer solutions of pH 4.0 and pH 7.0 were used to calibrate the pH meter before use. Periodically the calibration was checked using one of the buffer solutions and the pH meter was recalibrated. Once calibrated each sample was stirred with a glass rod and the pH electrodes were inserted and left for 30 seconds to stabilise before the readings were then taken. The electrode was then washed with de-ionised water to remove any contaminating material. This method (See Figure 3.6) has been adapted from that issued by the Ministry of Agriculture, Fisheries and Food (1986:99).

***Figure 3.6:*** *Overview of the pH and water extractable heavy metal tests*



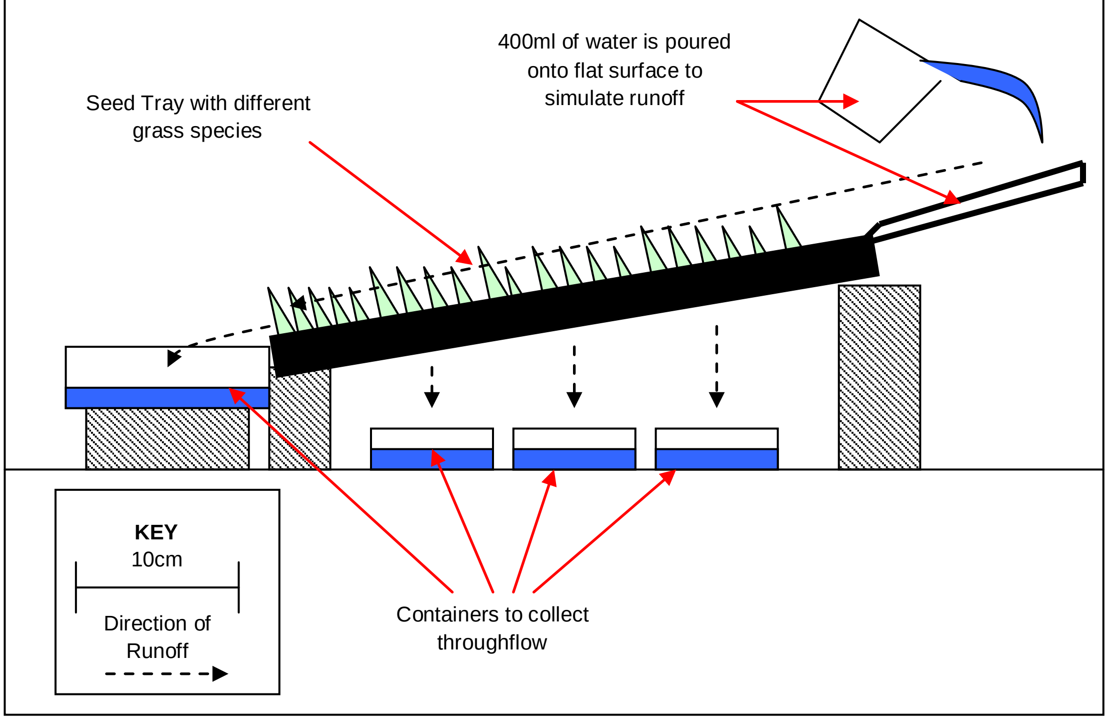
### 3.6.3 - Water Extractable Heavy Metals in Street Dust and Compost

Soil analysis can show the concentration of heavy metals found in a soil sample yet does not show the quantity that is potentially available to be accumulated by plant roots (Taiz and Zieger, 2006:82). However, with heavy metals being added to the compost in the form of street dust, there is likely to be an increase in bio-available heavy metals (Pierzynski et al. 2000:258). Extractable heavy metals were measured in order to determine the amount of heavy metals lost when the compost and street dust were watered, thus giving an indication of the quantity of metals that were leached out and potentially available. To measure this, 9.8cm$^3$ scoops of dried street dust and compost were taken and placed in separate conical flasks and 50ml of deionised water was then added. Deionised water was used to ensure consistency within the pot trials. There were four replicates for the street dust and compost samples. The conical flasks were shaken for one hour at 200rpm, after which the solutions were filtered into volumetric flasks for storage until they could be analysed by the ICP-OES in the same way as the other samples from the pot trials. Figure 3.6 shows this method which was adapted from the method issued by the Ministry of Agriculture, Fisheries and Food (1986:31).

## 3.7 - Hydraulic Retention Trials

The hydraulic retention trials were designed to test the ability of the various grass species to encourage infiltration by collecting water samples along the length of a simulated grassed surface. Each species was sown into individual seed trays (24cmx35cmx7cm) at the same density as the pot trials (See Figure 3.1). The trays were filled with 4Kg of John Innes seed compost. The trays were kept at a regulated temperature of approximately 25$^{o}$C (+/- 5$^{o}$C) in the Coventry University greenhouse, 52$^{o}$24$^{'}$ N 1$^{o}$30$^{'}$W (Google Earth). The trays were watered to field capacity with de-ionised water every 48hrs for four weeks allowing the grass to reach the recommended length of 100mm (Wood Ballard et al. 2007:253). For testing, the seed trays were placed into a larger container filled with 2 litres of de-ionized water. The trays were left for 60mins, allowing the water to be absorbed and to allow the soil to get to field capacity before being left for 24hrs They were then placed on a 3$^{o}$ incline with containers positioned underneath the drainage holes to capture through flowing water. A container was positioned at the bottom of the seed tray to capture any runoff water. 400ml of water was poured onto the top of the seed tray via a sheet of plastic which was designed to simulate the impermeable surface usually adjacent to a swale. 400ml was chosen to represent the runoff as it was sufficient to produce enough simulated runoff that would not be absorbed by the compost initially and provide enough water to prompt sufficient throughflow so samples could be measured. Smaller amounts tended not to produce any throughflow into the containers below, whilst larger amounts simply ran to the end of the tray and did not infiltrate into the compost. The water from each of the containers was measured to determine the proportion of the initial 400ml infiltrated at specific distances along the seed tray swale. Figure 3.7 shows the construction of the apparatus.

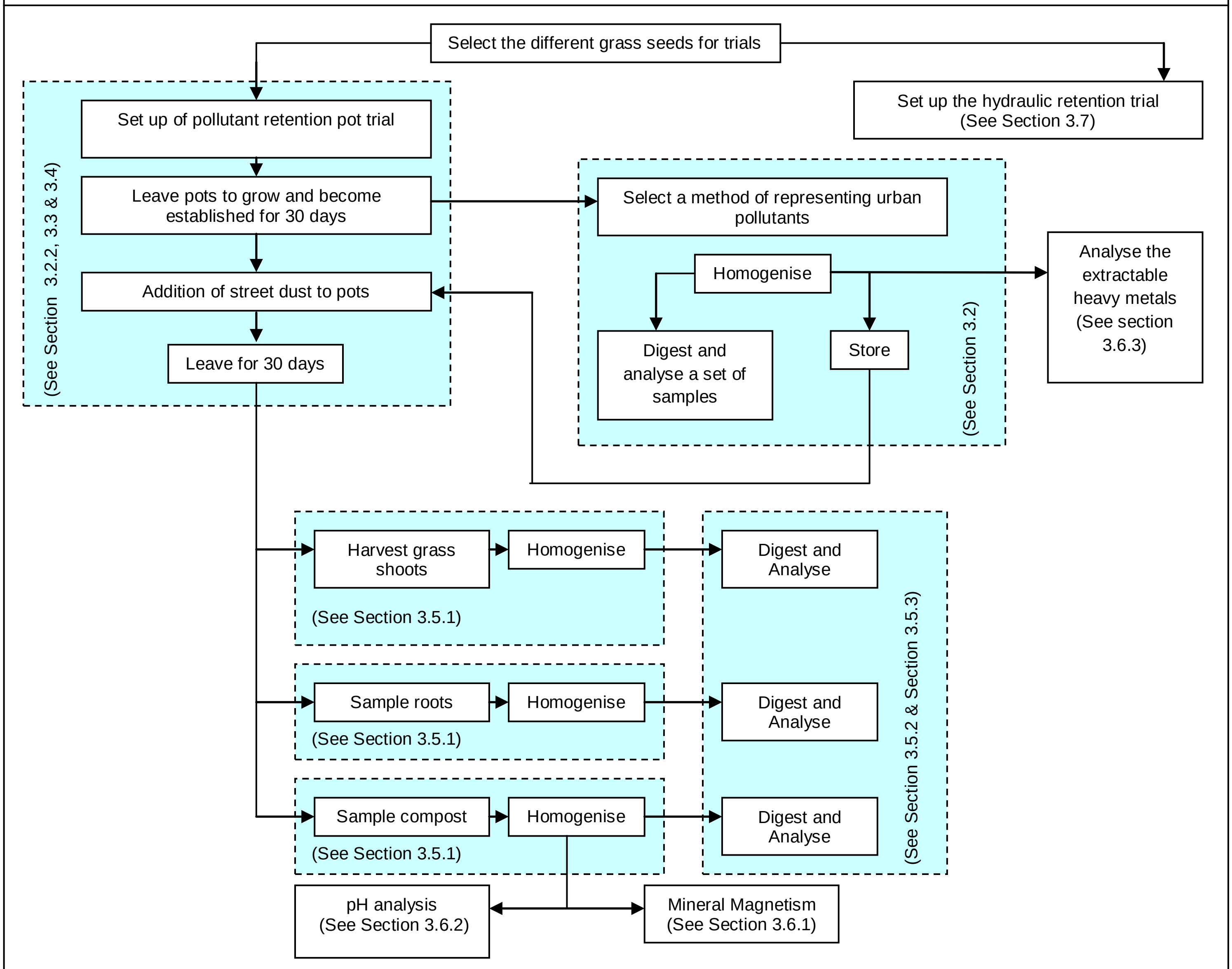
***Figure 3.7**: Setup of hydraulic retention trials*




## 3.9 - Conclusion

All the techniques described in this chapter are designed to show the pollutant remediation characteristics of the grasses with street dust application. Techniques such as microwave digestion and ICP-OES allow determination of the concentrations of heavy metals in the grass shoots, roots and compost to a high degree of accuracy. Other techniques such as mineral magnetism determined street dust distribution in the compost, reducing the time spent otherwise digesting all the compost in the trials pots. Measurement of pH offered explanations for different concentrations in shoots and roots. Lastly hydraulic retention trials offer information on the physical reaction of the grasses to flowing water and the presence of street dust. Together this provided the means to determine if a particular grass species was more suitable for use in swales or filter strips than another. The method is highlighted in the flow chart shown in Figure 3.8

***Figure 3.8:*** *A Flow Chart of the Complete Method*



# 4.0 Results

The method discussed in the previous chapter detailed the strategy employed to provide information on hydraulic and pollutant retention capabilities of seven grasses that could be suitable for vegetated surfaces in SUDS. It would also provide information regarding concentrations of Coventry's street dust which was compared to other studies as a check on the validity of using it as a simulated urban pollutant. These approaches address the aim and objectives of this study and enable an overall set of conclusions and recommendations to be derived.

This section provides the results of experiments conducted for this project. This includes the analysis and comparison of heavy metal concentrations in the pollution retention trials to determine whether the addition of different quantities of street dust had any effects. Other aspects such as pH, biomass weight and magnetic susceptibility of the compost profile were measured to analyse the impact of the street dust. Hydraulic retention trials were also conducted where quantities of water retained along the length of a seed tray were measured in order to provide an insight into the efficiency of different grass species at encouraging infiltration.

## 4.1 Heavy Metal Concentration in the Street Dust and Compost

Initial analysis examined concentrations of heavy metals in both the street dust and John Innes seed compost used in the pollutant retention trails. SPSS produced descriptive statistics and ranges for concentrations of each heavy metal being tested, which provided an understanding of the possible fluctuations in the street dust that was applied to the pots in the trial. The descriptive statistics can be seen in Table 4.1.

| *Table 4.1: Descriptive Statistics of Analysis of John Innes Seed Compost & Street Dust* | | | | | | |
|---|---|---|---|---|---|---|
| **Descriptive Statistics for John Innes Seed Compost** | | | | | | |
| | | Conc. (mg/kg) | | | | |
| | N | Range | Minimum | Maximum | Mean | Std. Deviation |
| Cadmium | 9 | .09 | .19 | .27 | .22 | .026 |
| Copper | 9 | 5.04 | 12.65 | 17.69 | 14.97 | 1.59 |
| Nickel | 9 | 1.53 | 5.33 | 6.86 | 6.16 | .51 |
| Lead | 9 | 15.58 | 18.57 | 34.16 | 22.91 | 4.99 |
| Zinc | 9 | 9.61 | 28.24 | 37.85 | 32.04 | 2.92 |
| **Descriptive Statistics for the Street Dust** | | | | | | |
| | | Conc. (mg/kg) | | | | |
| | N | Range | Minimum | Maximum | Mean | Std. Deviation |
| Cadmium | 32 | 3.45 | .68 | 4.13 | 1.55 | .95 |
| Copper | 32 | 148.99 | 123.47 | 272.45 | 185.91 | 31.71 |
| Nickel | 32 | 12.60 | 14.25 | 26.85 | 17.90 | 2.59 |
| Lead | 32 | 45.24 | 50.65 | 95.90 | 66.88 | 12.06 |
| Zinc | 32 | 149.79 | 261.42 | 411.21 | 314.59 | 30.06 |

| *Table 4.2: Average Water Extractable Heavy Metal Concentrations* | | |
|---|---|---|
| | (mg/L) | |
| Heavy Metal | Street Dust | Compost |
| Cd | 0.001 | 0.00075 |
| Cu | 0.016 | 0.02025 |
| Ni | 0.3808 | 0.0525 |
| Pb | 0.0074 | 0.0085 |
| Zn | 0.0388 | 0.022 |

Table 4.1 shows small heavy metal ranges in the compost. This is due to the compost being made to PAS 100 Standards that have strict regulations for heavy metal concentrations (Environmental Service Association n.d.). In comparison to the compost, the street dust shows much higher concentrations of heavy metals as well as much larger variations between samples, particularly for Cu, Pb and Zn. The water extractable tests were also conducted on both the street dust and compost (see Table 4.2) and show that with application of deionised water; very small amounts of heavy metals are actually leached out of both. The compost had slightly larger quantities of Cu and Pb leached from it compared to the street dust; whereas Cd and Zn were leached in slightly larger quantities from the street dust. Ni was the only heavy metal to be leached out in large qualities but only from the street dust.

## 4.2 Heavy Metal Concentration in the Compost Profile

The aim of the pollutant retention trial was to determine the distribution of heavy metals in the grass and compost before and after the addition of street dust. Sun and Davis (2007) determined that the majority of material in bio-retention systems was trapped in the soil. Therefore, the compost cores were used to validate this claim and determine whether concentrations were at harmful levels for growing vegetation. Figure 4.1 shows mean heavy metal concentrations in Layer B for each street dust treatment and all species.

Cd concentrations were very similar to that of the compost background levels shown in Table 4.1. There were two means shown in Figure 4.1 that were very different. The first was the 40g street dust treatment for the set of pots consisting of bare compost which registered at 0.9mg/kg, approximately four times that of the control pots (pots with no street dust applied). The second was for the control treatment for *A. capillaris syn.tenuis*, which was 0.43mg/kg showing the possible influences of particulate deposits in the street dust that could have high concentrations of heavy metals. For example; leakage from a battery could cause an increase in Cd concentrations in the compost. Ni and Pb had similar concentrations to the background readings shown in Table 4.1. Only Cu and Zn had slightly higher concentrations than the background (See Table 4.1). All the heavy metals exhibited an irregular set of concentrations with increasing street dust treatments. This could imply that perhaps street dust was not having an effect on Layer B. This is particularly evident for the control set (bare compost with no grass) which would be expected to increase with street dust treatments if it was having an effect. However, like the grass species, the heavy metal concentrations in the controls were similar to that of the background (Table 4.1) and irregular with street dust treatments. Table 4.3 shows ANOVA analysis which also indicates that the heavy metal concentrations did not significantly differ with street dust treatments. ANOVA analysis also showed that there was no significant difference in heavy metal concentrations with differing species.

***Table 4.3:*** *Two-way ANOVA Analysis of Compost Layer B Heavy Metal Concentrations*

| | Cd Compost | Cu Compost | Ni Compost | Pb Compost | Zn Compost |
|---|---|---|---|---|---|
| Grass Species | 0.459 | 0.447 | 0.459 | 0.421 | 0.465 |
| Street Dust | 0.460 | 0.368 | 0.497 | 0.490 | 0.453 |
| Grass Species* Street Dust | 0.575 | 0.351 | 0.557 | 0.609 | 0.512 |

*The mean difference is significant at the 0.05 level

With two-way ANOVA analysis showing that neither species nor the street dust treatments showed significantly different heavy metal concentrations, interpretations were based upon visual analysis of Figure 4.1. Firstly, it shows that the bare compost set of pots were, generally, similar in concentration to all the other species for each heavy metal. However, there are cases where one particular treatment shows much larger concentrations that the other samples. An example would be 40g street dust treatment for Cd which possesses a mean concentration approximately three times larger than the other samples from different species. The standard error bars also provide an insight into the large amounts of variation within each set of samples, especially for treatments with high mean values, and may be related to the variations found in the street dust which was applied. This means that the bare compost is accumulating a similar amount of heavy metals as the pots containing grass, a possible indication that the street dust is only penetrating to Layer B in small quantities. However, the variations illustrated by the error bars do show that perhaps small amounts of street dust are influencing the concentration in Layer B therefore affecting the mean concentration. Figure 4.1 also shows that *A. capillaris syn.tenuis* consistently had the highest concentrations of each heavy metal, illustrating that individual grass characteristics may be important. *A. canina* and *P. pratensis* were consistently found to have smaller heavy metal concentrations to the majority of the other species, something that is displayed in Figure 4.1. However, these species are not shown to be significantly smaller from a statistical perspective. As the street dust did not appear to cause significant differences in the concentration of Layer B the differences may be attributed to the accumulation of heavy metals by the grass. *A. canina* and *P. pratensis* consistently have the lowest metal concentrations, which may suggest that these species are accumulating more heavy metals than the other grasses, therefore removing them from the compost.

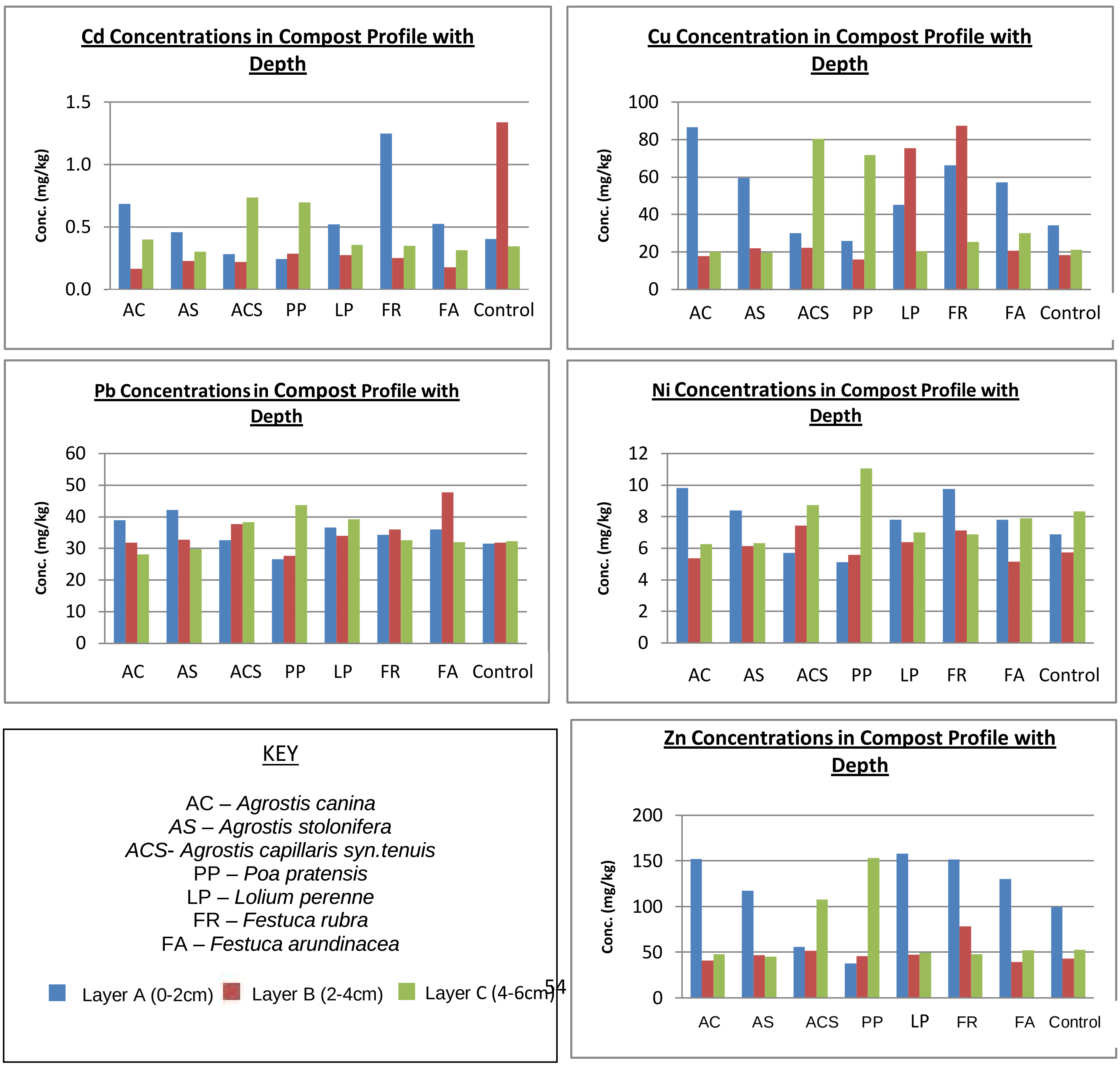
The street dust concentration did not have an effect on heavy metal accumulation in Layer B possibly because it did not wash down through the top layer of compost. The concentrations, in particular of Cd and Ni, are similar to that of background. To determine whether the street dust penetrated the upper layer of compost and its distribution in the compost layers, an investigation was undertaken of the upper layer (Layer A) and the bottom layer (Layer C). The results of this investigation are shown in the following section.

***Figure 4.1:*** *Mean Heavy Metal Concentration Compost Layer B*

### 4.2.1 Investigation of Metal Concentration in the Upper and Lower Compost Layers

It was hypothesised that the street dust might not have migrated into the middle layer of the core but had remained on the surface or in the upper parts of the compost. Samples from Layers A and C were collected to provide a more detailed picture of the heavy metal distribution in the compost. Figure 4.2 shows the mean concentration of heavy metals from each layer for the 40g street dust treatment.

***Figure 4.2:*** *Heavy Metal Concentrations in the Compost Profile with 40g Street Dust Treatment*



The majority of results in Figure 4.2 show that Layer A had higher concentrations than Layer B which was more extensively sampled during the pollutant retention trial. The compost control and *P. pratensis* show most consistently that Layer C had the highest heavy metal concentrations. This could possibly be attributed to the distribution of the majority of the roots either accumulating heavy metals from the surface or the root structure not restricting the movement of street dust as much as the other species.

Table 4.4 shows the results of the one way ANOVA analysis which was performed in order to determine whether a particular species had significantly different heavy metal concentrations with depth. The post hoc tests (Table 4.5) showed which of the compost layers were significantly different to each other as well as which had the largest concentration for each heavy metal and species. *A. stolonifera*, *P. pratensis* and *A. canina* were the only species to have significant difference in concentration with depth for all the heavy metals whilst the other species all had at least one significant difference in a heavy metal with depth. For the majority of species, the largest concentrations were found in Layer A, with Layers B and C being significantly less. However, for *P. pratensis* showed Layer C contained the highest concentrations, which was significantly different from all species except *A. capillaris syn.tenuis* which also had the highest concentration for Ni and Zn in Layer C. However, there were no significant differences between the concentration of Cd, Cu and Pb with depth for *A. capillaris syn.tenuis*. Obviously with street dust being applied to the surface, it was hypothesised that Layer A would have the highest concentrations.

***Table 4.4:*** *One-way ANOVA of Heavy Metal Concentrations with Depth Down Compost Profile*

| Species | Cd | Cu | Ni | Pb | Zn |
|---|---|---|---|---|---|
| *Agrostis capillaris syn.tenuis* | - | - | 0.047 | - | 0.028 |
| *Agrostis stolonifera* | 0.000 | 0.000 | 0.019 | 0.013 | 0.000 |
| *Agrostis canina* | 0.012 | 0.000 | 0.002 | 0.002 | 0.000 |
| *Lolium perenne* | 0.001 | - | - | - | 0.002 |
| *Festuca rubra* | - | - | - | - | - |
| *Poa pratensis* | 0.010 | 0.000 | 0.000 | 0.000 | 0.000 |
| *Festuca arundinacea* | - | 0.000 | 0.000 | - | 0.000 |
| Control (Bare Compost) | 0.000 | 0.000 | 0.014 | - | 0.000 |

NB: Only the significant values have been displayed. Species with no value showed no significant difference with depth

| ***Table 4.5:*** *Post Hoc Results Showing Layer of Compost with Highest Concentrations* | | | | | |
|---|---|---|---|---|---|
| Species | Cd | Cu | Ni | Pb | Zn |
| *Agrostis capillaris syn.tenuis* | - | - | Layer C | - | Layer C |
| *Agrostis stolonifera* | Layer A | Layer A | Layer A | Layer A | Layer A |
| *Agrostis canina* | Layer A | Layer A | Layer A | Layer A | Layer A + Layer C |
| *Lolium perenne* | Layer A | - | - | - | Layer A |
| *Festuca rubra* | - | - | - | - | - |
| *Poa pratensis* | Layer C | Layer C | Layer C | Layer C | Layer C |
| *Festuca arundinacea* | - | Layer A | Layer A + Layer C | - | Layer A |
| Control (Bare Compost) | Layer A | Layer A | Layer C | - | Layer A |
| NB: Only the significant values have been displayed. Species with no value showed no significant difference with depth | | | | | |

However, with the variation in the layer which had the highest concentration with species it is possible that either the grasses are taking up heavy metals differently or that street dust is migrating through the profile for certain species. Ni indicates that it might be particularly mobile since Layer C control show significantly different concentrations to the other layers. In order to validate whether street dust had migrated down profile, mineral magnetic analysis was conducted. These findings are displayed in the next section.

### 4.2.2: Mineral Magnetism of the Compost Profile

Table 4.6 shows that the average low frequency susceptibility of the compost was 0.13 $10^{-6}m^3kg^{-1}$, whereas the street dust was much higher with an average of 3.9$10^{-6}m^3kg^{-1}$. The average values for each species and for layer are also displayed in Table 4.6, which showed that Layer A had the highest readings in comparison to plain compost. This is expected as the street dust was applied to the surface. Layer B has a lower susceptibility than Layer A; however, these readings are higher than compost readings indicating that street dust had passed into Layer B. Layer C had slightly higher susceptibility than Layer B suggesting that street dust either migrated down the profile or may have travelled down the sides of pots, bypassing the compost.

| ***Table 4.6:*** *Mean Susceptibility Readings* | | | | |
|---|---|---|---|---|
| | | Low Freq Susceptibility Readings ($10^{-6}m^3kg^{-1}$) | | |
| N° of Samples (n) | | **(Layer A)** | **(Layer B)** | **(Layer C)** |
| 5 | *A. capillaris syn.tenuis* Mean | 0.63 | 0.27 | 0.30 |
| 5 | *A. stolonifera* Mean | 0.79 | 0.24 | 0.26 |
| 5 | *A. canina* Mean | 1.00 | 0.49 | 0.41 |
| 5 | *L. perenne* Mean | 0.67 | 0.29 | 0.27 |
| 5 | *F. arundinacea* Mean | 0.74 | 0.29 | 0.74 |
| 5 | *F. rubra* Mean | 0.68 | 0.26 | 0.2 |
| 5 | *P. pratensis* Mean | 0.77 | 0.21 | 0.23 |
| 5 | Control Mean | 1.06 | 0.30 | 0.30 |
| 10 | Mean Compost | **0.13** | | |
| 10 | Mean Street Dust | **3.86** | | |

The size of street dust treatment seemed to have had an effect on the susceptibility readings with the street dust treatment dictating the reading that was produced; the highest treatment (40g street dust) produced the highest susceptibility readings and lower values with decreasing street dust treatments. With the smaller treatments (5g street dust and 10g street dust) the readings were similar to each other yet still larger than the compost, which is to be expected as the street dust treatments increase exponentially. The 5g and 10g street dust treatments only represent 1.25% and 2.5% of the volume of compost in each pot which makes little difference overall to the magnetic susceptibility, which is illustrated by mineral magnetic results shown in Figure 4.3 Only *A. capillaris syn.tenuis* showed no increase in magnetic susceptibility in the upper segment with increasing street dust treatments apart from the 40g treatment which displayed similar susceptibility results to the other species.

In conclusion, susceptibility measurements established that street dust mainly accumulated in the top 2cm (Layer A) of the compost profile with finer material migrating through the compost profile over time. Some finer material is trapped in Layer B; however, a larger proportion of the street dust is found at the bottom (Layer C) of the compost profile. With the distribution of heavy metals in the compost now known, the next stage was to analyse the plant roots (Section 4.3) and shoots (Section 4.4) to determine whether the heavy metals from the compost had accumulated in these tissues.

*Figure 4.3: Compost Low Frequency Magnetic Susceptibility Results for All Species*

## 4.3 -Heavy Metals Concentration in Roots

Roots are important in the up-take of heavy metals by grasses and are the main pathway for heavy metal movement from the compost to the shoots (Kalis et al. 2007:335). The ability to remove nutrients from the compost would indicate more potential for heavy metal removal if grown in vegetative SUDS. Figure 4.4 shows the average heavy metal concentrations in roots. There appears to be no increase in heavy metal concentrations in the roots with increasing street dust treatment. Instead the increases in concentration are irregular and not determined by the quantity of the street dust treatment. For example, the Pb 10g street dust treatment for *F. arundinacea* produced an average concentration of approximately 32mg/kg; double that of any of the other street dust treatments. This can be seen with other heavy metals for all species. This irregular set of heavy metal concentrations could be related to what is actually being sampled. Heavy metals might be contained in the roots themselves but also attached to the surface either as dissolved heavy metals that accumulate on the root or as compost that might have remained despite the efforts to reduce this outlined in the method section. The street dust treatments caused no significant difference in concentrations (Table 4.7) however, all the heavy metals did show significant difference with species illustrating that species may accumulate different amounts of heavy metals which is shown by Figure 4.4 with species such as *L. perenne* for Pb.

***Table 4.7:*** *Two-way ANOVA Results for Root Concentrations*

| | Cd Roots | Cu Roots | Ni Roots | Pb Roots | Zn Roots |
|---|---|---|---|---|---|
| Grass Species | **0.006** | **0.000** | **0.001** | **0.000** | **0.000** |
| Street Dust | 0.579 | 0.069 | 0.94 | 0.767 | 0.120 |
| Grass Species* Street Dust | 0.381 | 0.582 | 0.54 | 0.553 | 0.262 |
| *The mean difference is significant at the 0.05 level | | | | | |

Although ANOVA suggests that street dust treatment does not cause significant difference for any of the heavy metals, the effect could have been obscured by the number of species being simultaneously connected in the two-way ANOVA. By examining Figure 4.4 it seems possible that they do have some effect with Cu in the roots for *A. capillaris syn.tenuis*, *A. stolonifera* and *A. canina* showing an increase in relation to the control with increasing street dust treatments although it is rather irregular. Zn exhibits a similar pattern for *A. stolonifera* and *A. canina*. The ANOVA analysis showed values for Cu of 0.069 and Zn of 0.120 therefore, it was decided that the ANOVAs were close enough to significant to warrant a separate one way ANOVA for each species. These one way ANOVA results are displayed in Table 4.8.

***Figure 4.4:*** *Mean Heavy Metal Concentration in the Roots*

| ***Table 4.8:*** *One-way ANOVA Analysis for Root Heavy Metal Concentrations* | | | | | |
|---|---|---|---|---|---|
| Species | Cd | Cu | Ni | Pb | Zn |
| *A. capillaris syn.tenuis* | | **0.032** | | | 0.301 |
| *A. stolonifera* | | 0.608 | | | 0.606 |
| *A. canina* | **0.024** | 0.426 | 0.554 | 0.352 | 0.791 |
| *L. perenne* | | 0.677 | | | 0.446 |
| *F. rubra* | | 0.818 | | | 0.061 |
| *P. pratensis* | | n/a | | | n/a |
| *F. arundinacea* | | 0.151 | | | 0.676 |
| **Significant Post Hoc Results (Cu for *A. capillaris syn.tenuis* )** | | | **Significant Post Hoc Results (Cd for *A. canina*)** | | |
| **Treatments** | **Sig.** | | **Treatments** | **Sig.** | |
| Control | 5g SD | 0.018 | 40g SD | 20g SD | 0.016 |
| | 10g SD | 0.015 | | 5g SD | 0.012 |
| | 20g SD | 0.004 | | Control | 0.005 |
| | 40g SD | 0.009 | | | |

There are only two significant results shown in Table 4.8: Cu for *A. capillaris syn.tenuis* (0.032) and Cd for *A. canina* (0.024). The post hoc tests show that for *A. capillaris syn.tenuis* all of the street dust treatments produced significantly different Cu concentrations compared to the controls. For Cd in *A. canina* the significant differences are shown for the 40g street dust treatment against the control, 5g and 20g street dust treatment. When comparing these to Figure 4.4 it is possible that the ANOVA may be influenced by high concentrations and variability in the street dust. *A. capillaris syn.tenuis,* which showed a significant result for Cu, could be influenced by high concentrations in the 40g street dust treatments with the other treatments producing similar mean concentration in root samples. Species such as *A. canina* do not show significant differences for Cu and Zn for street dust treatments, which was possibly due to the large amount of variation displayed in Figure 4.4, illustrated by the standard error bars. This large variation suggests that there was not an influence with treatment because of the irregular results. As previously stated the variation in concentration represented by the error bars could have been caused by compost or street dust attached to the root that was not removed by the washing process. It is possible that particles of street dust may not even have associated soluble heavy metals and therefore when attached to the root they may not have any effect on heavy metal concentrations.

Heavy metal concentrations in the roots are shown to differ significantly with species (Table 4.7); post hoc tests allowed the different species to be grouped together depending on whether there were significant differences between each other (Table 4.9). Group 1 has species with the highest concentrations and Groups 2-4 subsequently decrease in concentration. Species in one group are significantly different from the species in the other groups. When more than one species was grouped together they were not significantly different from each other but significantly different from both the groups above and below them. Bent grasses were frequently in the top groups showing that perhaps they were capable of taking up more of the essential heavy metals (Cu, Ni and Zn). For Pb the majority of species are in one group indicating a similar level of uptake due to Pb being non-essential (Hopkins and Hüner, 2008:66). The next section details the heavy metal concentrations for shoots and whether the addition of street dust had an effect.

***Table 4.9:*** *Grouped Species for Root Concentrations Using Post Hoc Testing*

| | Cd-Roots | Cu-Roots | Ni-Roots | Pb-Roots | Zn-Roots |
|---|---|---|---|---|---|
| Group 1 | AC | AC, AS, FR | AS | AS, FR, AC, ACS | ACS |
| Group 2 | ACS, AS | ACS | ACS, FR, FA AC | LP, FA | AS, AC, LP |
| Group 3 | FR | LP, FA | LP | | FR |
| Group 4 | LP | | | | FA |
| Group 5 | FA | | | | |

**ACS**= *Agrostis capillaris syn.tenuis;* **AS** = *Agrostis stolonifera;* **AC** = *Agrostis canina*
**LP** = *Lolium perenne;* **FR** = *Festuca rubra;*
**FA** = *Festuca arundinacea*

## 4.5 -Heavy Metals Concentration in Shoots

The concentration of metals in the shoots is the last piece of information to determine the distribution of heavy metals in the pollutant retention trial and understand the distribution of heavy metals between the grass species. Higher concentrations in the shoots would allow for the removal of contaminants by mowing. However, if concentrations are low it may suggest that translocation of heavy metals to the shoots is not an effective method of pollutant retention (Sun and Davis, 2007:1608). The results of this section are therefore important not only for determining the distribution of heavy metals but also to determine whether any grass species performed particularly well, thus helping the recommendation of grasses that are suitable for vegetative devices. Figure 4.5 shows the mean heavy metal concentrations found in the grass shoots.

For Cu, Pb and Zn (See Figure 4.5) there is a fairly progressive increase in concentration with increasing street dust treatment for the majority of species. Only *A. capillaris syn.tenuis* and *A. canina* show irregular increases in concentrations with increasing street dust treatments. Another trend shown by *A. canina* and *A. capillaris syn.tenuis* is that they consistently have the highest concentrations of heavy metals, especially for Ni which was up to ten times that of the other species. Due to this dramatic difference *A. canina* and *A. capillaris syn.tenuis* samples were re-tested producing similar results indicating that the ICP-OES was functioning properly. Although *A. capillaris syn.tenuis* had a high concentration of heavy metals there was often little increase compared to the control (See Figure 4.5). For example, Cu concentrations for the 5g and 20g street dust treatments with *A. capillaris syn.tenuis* were similar to the control with the mean concentrations being within 1mg/kg of the control, 5g and 10g treatments. The value for the 10g treatment was half that of the control, whereas that for the 40g treatment was nearly three times the control concentration. However, the standard error bars show that there are large variations in Cu especially with the 40g treatment that would influence the mean concentrations shown. For the rest of the metals (See Figure 4.5), concentrations for all species were generally higher than the control except for Cd and Ni where there was little to no increase. Again there also appears to be variation in the results with *A. capillaris syn.tenuis* and *A. canina* generally showing the largest standard error bars. Some individual treatments show the potential influence of the variable nature of street dust, for example, the 10g street dust treatment for *A. stolonifera* appears to be higher than the other results and also displays larger standard error bars than the other treatments for this species, for all metals.

***Figure 4.5:*** *Mean Heavy Metal Concentrations in the Dried Grass Shoots*

| ***Table 4.10**: Two-way ANOVA Results for Shoot Concentrations* | | | | | |
|---|---|---|---|---|---|
| | Cd Shoots | Cu Shoots | Ni Shoots | Pb Shoots | Zn Shoots |
| Grass Species | 0.477 | **0.000** | **0.000** | 0.238 | **0.000** |
| Street Dust | 0.469 | **0.001** | 0.059 | 0.347 | **0.010** |
| Grass Species*Street Dust | 0.472 | **0.021** | **0.001** | 0.466 | 0.055 |
| *The mean difference is significant at the 0.05 level | | | | | |

| ***Table 4.11**: Two-way ANOVA Results for Shoot Concentrations (Excluding Agrostis canina)* | | | | | |
|---|---|---|---|---|---|
| | Cd Shoots | Cu Shoots | Ni Shoots | Pb Shoots | Zn Shoots |
| Grass Species | 0.442 | **0.000** | **0.000** | 0.094 | **0.000** |
| Street Dust | 0.412 | **0.001** | 0.216 | **0.000** | 0.070 |
| Grass Species*Street Dust | 0.478 | 0.391 | 0.076 | 0.421 | 0.172 |
| *The mean difference is significant at the 0.05 level | | | | | |

ANOVA analysis was performed on the metal concentrations in grass shoots (Table 4.10), showing that all the heavy metals except Cd and Pb show significant differences between grasses and Cu and Zn showed significant differences between street dust treatments. However, there is also a significant interaction between species and street dust (highlighted in red in Table 4.10) suggesting that neither species nor street dust is acting independently to influence the heavy metal concentrations in the shoots. This makes it difficult to determine the individual factor causing the differences in heavy metal concentrations. Figure 4.5 shows that *A. canina* maybe the species influencing this set of results as it demonstrated larger metal concentration with street dust treatments for all elements. Two-way ANOVA analysis was therefore performed on the shoots with *A. canina* excluded (See Table 4.11). The analysis showed that for all the grass species, significant values remained the same (i.e. Cu, Ni and Zn) but now only Cu and Pb showed significant differences with street dust treatments. By excluding *A. canina,* there were no significant interactions between street dust treatments and species. Significant results for the post hoc analysis for street dust are shown in Table 4.12 & 4.13. The 20g and 40g street dust treatments for Cu showed significant difference to the control with the 40g street dust treatment also being significantly higher than the 5g and 10g treatments. This indicates that larger amounts of street dust were required to change shoot concentrations. A similar pattern is found with Pb although there seems to be less variation with the street dust treatments with the 10, 20g and 40g treatments producing statistically similar results. This could be related to the variation shown by the standard error bars (See Figure 4.5) indicating the variability in street dust concentrations.

| ***Table 4.12:*** *Post Hoc Results for Heavy Metal Concentrations in Shoots in terms of Street Dust Treatment (Excluding A. canina)* | | | | |
|---|---|---|---|---|
| **Heavy Metal** | **Street Dust Treatment (I)** | **Street Dust Treatment (J)** | **Mean Difference (I-J) (mg/kg)** | **Sig.** |
| Cu | 20g | Control | 5.787 | 0.013 |
| | | | | |
| | 40g | Control | 9.692 | 0.000 |
| | | 5g | 7.475 | 0.002 |
| | | 10g | 5.318 | 0.024 |
| Pb | 10g | Control | 3.829 | 0.000 |
| | | 5g | 2.407 | 0.012 |
| | 20g | Control | 2.482 | 0.009 |
| | 40g | Control | 3.662 | 0.000 |
| | | 5g | 2.240 | 0.018 |

The post hoc results related to species (Table 4.13) showed that *A. capillaris syn.tenuis* had consistently higher concentrations than the other species for Cu, Ni and Zn. Results for *P. pratensis* showed that it had similar heavy metal concentrations to *A. capillaris syn.tenuis* for Cu and Zn. It had higher concentrations with all metals for the majority of species except *A. capillaris syn.tenuis*. *P. pratensis* was similar to all the other species for Ni with *A. capillaris syn.tenuis* having significantly higher concentrations of Ni in the shoots. Figure 4.5 shows that Zn increases in concentration with increasing treatments but for certain species such as *L. perenne* and *F. rubra* the standard error bars were smaller compared to the other species. However, ANOVA results may be influenced by other species such as *A. capillaris syn.tenuis* and *A. stolonifera*. *A. capillaris syn.tenuis* which showed larger variations in concentrations found in the shoots. Figure 4.5 again shows standard error bars for the 5g street dust treatment of approximately 20mg/kg either side of the mean concentration.

Additional analysis was also conducted for Zn which was just outside the 95% confidence interval with a significance of 0.070 (See Table 4.11). It was thought that the two-way ANOVA might have obscured the significance due to the number of species being simultaneously analysed. Figure 4.5 illustrated that there seemed to be a relationship between all the species but *A. capillaris syn.tenuis* with street dust treatments and increasing concentrations. Therefore two-way ANOVA analysis was performed with both

*A. canina* and *A. capillaris syn.tenuis* removed. The results (Table 4.14) showed that street dust treatments caused significant differences in Zn concentrations in the shoots compared to the control. Post hoc tests (Table 4.14) illustrate the progressive step up in concentrations shown in Figure 4.5.

***Table 4.13:*** *Post Hoc Results for Heavy Metal Concentrations in Shoots in terms of Species (Excluding A. canina)*

| Grass Species (I) | Grass Species (J) | Heavy Metal | Mean Difference (I-J) (mg/kg) | Sig. |
|---|---|---|---|---|
| *A. capillaris syn.tenuis* | *F.arundinacea* | Cu | 11.827 | 0.000 |
| | *F. rubra* | | 7.837 | 0.003 |
| | *L. perenne* | | 7.441 | 0.004 |
| | *A. stolonifera* | | 6.566 | 0.011 |
| | *A. stolonifera* | Ni | 1386.161 | 0.000 |
| | *L. perenne* | | 1470.627 | 0.000 |
| | *P. pratensis* | | 1514.283 | 0.000 |
| | *F. rubra* | | 1526.599 | 0.000 |
| | *F.arundinacea* | | 1537.859 | 0.000 |
| | *P. pratensis* | Zn | 14.314 | 0.002 |
| | *A. stolonifera* | | 28.452 | 0.000 |
| | *L. perenne* | | 33.776 | 0.000 |
| | *F.arundinacea* | | 44.099 | 0.000 |
| | *F. rubra* | | 45.611 | 0.000 |
| *A. stolonifera* | *F.arundinacea* | Cu | 5.260 | 0.039 |
| | *F.arundinacea* | Zn | 15.646 | 0.001 |
| | *F. rubra* | | 17.158 | 0.000 |
| *L. perenne* | *F.arundinacea* | Zn | 10.322 | 0.023 |
| | *F. rubra* | | 11.834 | 0.009 |
| *P. pratensis* | *A. stolonifera* | Cu | 9.740 | 0.000 |
| | *L. perenne* | | 10.616 | 0.000 |
| | *F. rubra* | | 11.010 | 0.000 |
| | *F.arundinacea* | | 15.000 | 0.000 |
| | *A. stolonifera* | Zn | 14.138 | 0.002 |
| | *L. perenne* | | 19.462 | 0.000 |
| | *F.arundinacea* | | 29.784 | 0.000 |
| | *F. rubra* | | 31.297 | 0.000 |

| ***Table 4.14:*** *Two-way ANOVA and Post Hoc Results for Zn Concentrations in Shoots (Excluding A. capillaris syn.tenuis & A. canina)* | | | |
|---|---|---|---|
| | Zn Shoots | | |
| Grass Species | **0.000** | | |
| Street Dust | **0.000** | | |
| Grass Species* Street Dust | 0.756 | | |
| **Post Hoc Results for Heavy Metal Concentrations in Shoots (Excluding *A. capillaris syn.tenuis* & *A. canina*)** | | | |
| Street Dust Treatment (I) | Street Dust Treatment (J) | **Mean Difference (I-J) (mg/kg)** | **Sig.** |
| 5g | Control | 9.235 | 0.007 |
| | | | |
| 10g | Control | 14.794 | 0.000 |
| | | | |
| 20g | 5g | 6.816 | 0.046 |
| | Control | 16.050 | 0.000 |
| | | | |
| 40g | 5g | 8.185 | 0.017 |
| | Control | 17.420 | 0.000 |
| | Control | 17.900 | 0.000 |

As a measure of the difference between *A. canina* and the other species a separate one way ANOVA analysis was applied to the different treatments individually (Table 4.15). Firstly, it illustrated that the number of significant differences for each heavy metal, with species, increased with increasing concentration of street dust treatments. Post hoc analysis of these significances (See Appendix II) shows that for the controls, *A. capillaris syn.tenuis* had the highest concentrations and was significantly different from the majority of species for Cd and Zn. *A. canina* also possesses similar significant differences to the majority of species in comparison with the control treatment. With increasing street dust treatments, *A. canina* becomes significantly larger than the majority of the species in Cu, Ni, Pb and Zn. Two other species that stand out are *A. capillaris syn.tenuis* and *P. pratensis* with the 20g street dust treatment. *P. pratensis* shows significant differences from the majority of the other species for Cu and Pb, with only *A. canina* having higher concentrations. *P. pratensis* also showed significantly higher concentrations for Zn. *A. capillaris syn.tenuis* exhibited significant differences with Ni, showing potential to accumulate Ni in the shoots compared to the other species. Other than Ni, *A. capillaris syn.tenuis* showed significant differences from other species for Cu with the larger treatments (10g, 20g and 40g street dust). *A. capillaris syn.tenuis* was only consistently significantly different from *F. arundinacea* with these treatments. Perhaps the variability in street dust metal concentrations affected *A. capillaris syn.tenuis* since it was consistently higher than most species because it may have had more available heavy metals between treatments. The species not mentioned showed no significant difference between each other for the majority of the one-way ANOVA analysis, indicating similar effects with street dust treatments.

***Table 4.15****: One-way ANOVA of Different Street Dust Treatments*

| Heavy Metals | Control | 5g SD | 10g SD | 20g SD | 40g SD |
|---|---|---|---|---|---|
| Cd | **0.047** | 0.451 | 0.221 | **0.040** | **0.027** |
| Cu | 0.243 | **0.005** | **0.000** | **0.000** | **0.002** |
| Ni | 0.081 | **0.000** | **0.000** | **0.000** | **0.000** |
| Pb | 0.198 | 0.095 | **0.003** | **0.000** | 0.385 |
| Zn | **0.001** | **0.000** | **0.000** | **0.000** | **0.000** |

Using the post hoc tests of species (Table 4.13) and the knowledge that *A. canina* had the highest concentrations in the shoots for all heavy metals, Table 4.16 was constructed showing species grouped together with those that exhibited the highest concentrations in Group 1, down to Group 7 representing those with significantly decreasing concentrations. This gave an indication of a possible ranking of species for accumulation of each heavy metal.

***Table 4.16:*** *Grouped Grass Species for Shoot Concentrations Using Post Hoc Testing*

| | Cu- Shoots | Ni-Shoots | Zn-Shoots |
|---|---|---|---|
| Group 1 | AC | AC | AC |
| Group 2 | ACS, PP | ACS | ACS |
| Group 3 | AS, LP, FA and FA | AS, LP, FR, PP and FA | PP |
| Group 4 | - | - | AS |
| Group 5 | - | - | LP |
| Group 6 | - | - | FA |
| Group 7 | - | - | FR |

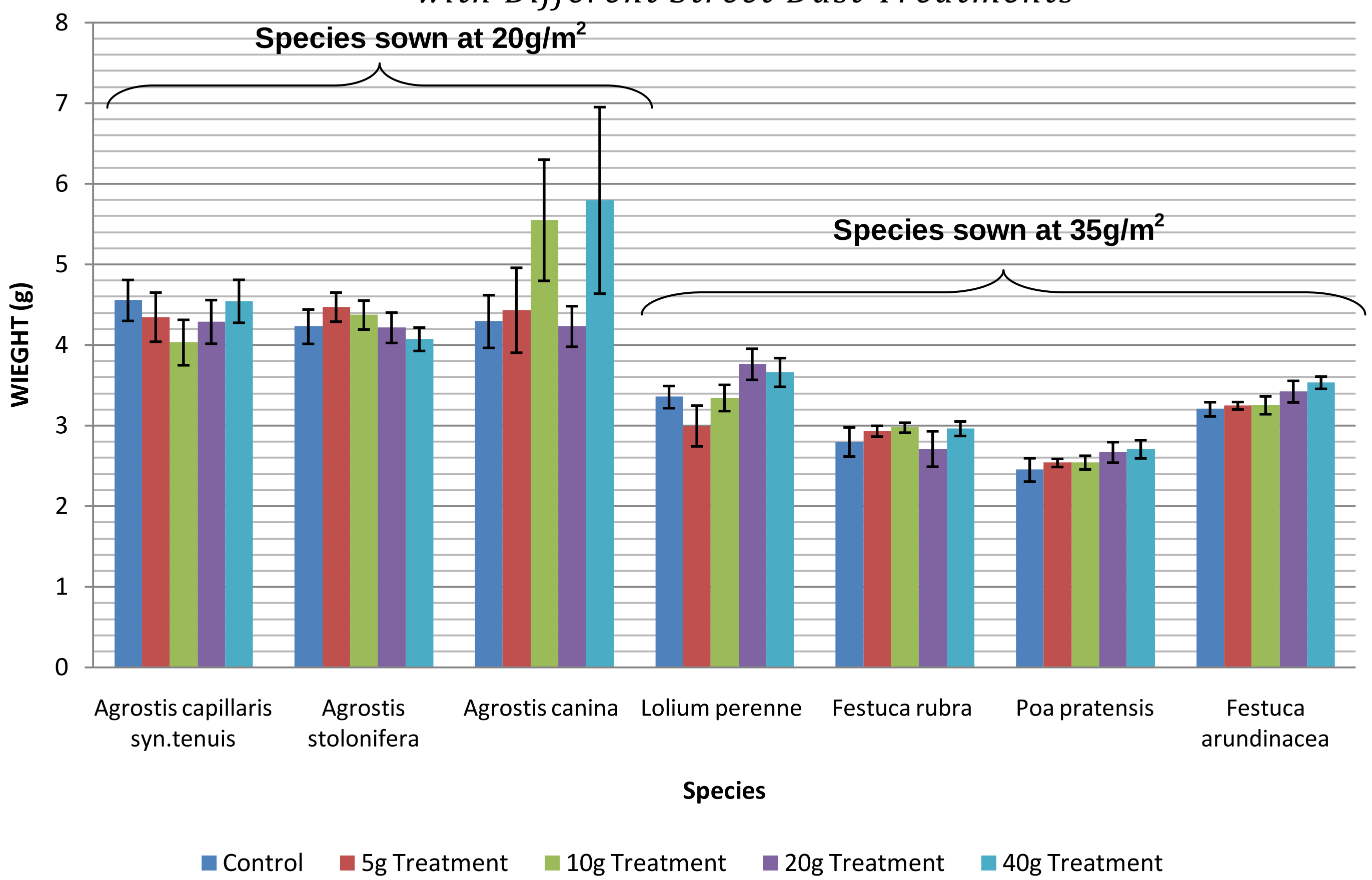
***ACS***= *Agrostis capillaris syn.tenuis;* **AS** = *Agrostis stolonifera;* **AC** = *Agrostis canina*
**LP** = *Lolium perenne;* **FR** = *Festuca rubra;* **PP** = *Poa pratensis*
**FA** = *Festuca arundinacea*

With the concentrations in the roots and shoots established, links between the soil, roots and shoots needed to be determined and a clear step based approach utilised to explain heavy metal uptake. Kalis et al. (2007) detailed such an approach for *L. perenne* that described the movement of heavy metals within the soil and the relationship that this had to root and shoot concentration. A similar approach may be applicable other grass species. As a test of suitability, the biomass was analysed to determine whether the addition of street dust increased production. Studies have identified street dust addition as promoting production of biomass and hence heavy metal accumulation (Sun and Davis, 2007:1608). The results are displayed in the following section.

## 4.6 -Dry Biomass

Figure 4.6 shows the average biomass per species for different treatments. The biomass represents the yield of grass that was produced by each pot. The two factors that could affect the yield are the different treatments and the natural variation in grass yield by different species. Natural variation is reflected in the control biomass yields as well the standard error bars. The Bent varieties of grass show higher biomass yields than the other grass species, a factor related to the different sowing densities which are illustrated above the data on Figure 4.6.

***Figure 4.6*** *- Mean Biomass Produced by the Different Grass Species with Different Street Dust Treatments*



Different treatments could lead to accumulations of heavy metal concentrations in the growing plant causing toxicity and negative effects on grass yields. However, due to the street dust containing high amounts of Cu and Zn, which are essential micronutrients, this could promote growth and therefore increased grass yield. To determine whether the street dust caused significant change in grass yields, a two-way ANOVA analysis was performed. Due to the different sowing densities, separate analysis were performed on the Bents and the other four non-bent grasses with the results shown in Table 4.17.

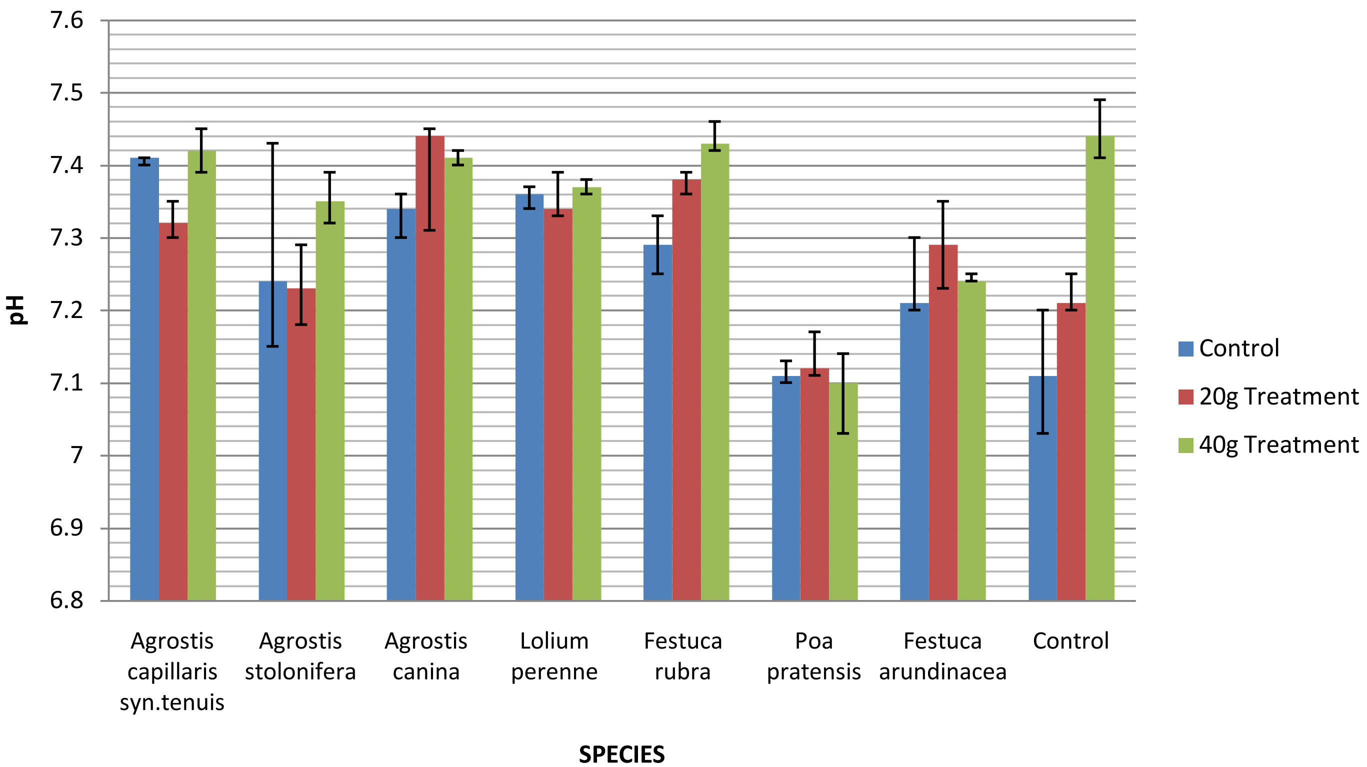
| ***Table4.17:*** *Two way ANOVA Results for Biomass Yield* | | | |
|---|---|---|---|
| **Bents (*A. capillaris syn.tenuis*, *A. stolonifera* and *A. canina*)** | | **Non-Bent Grasses (*L. perenne*, *F. rubra*, *P. pratensis* and *F.arundinacea*)** | |
| Factors | Sig. | Factor | Sig. |
| Grass Species | 0.081 | Grass Species | **0.000** |
| Street Dust | 0.528 | Street Dust | **0.019** |
| Grass Species * Street Dust | 0.296 | Grass Species * Street Dust | 0.233 |
| | | | |
| **Significant Post hoc Results for Species with Non-Bent Grasses** | | | |
| Grass Species (I) | Grass Species (J) | Mean Difference (I-J) | Sig. |
| *L. perenne* | *F. rubra* | .538 | .000 |
| | *P. pratensis* | .832 | .000 |
| *F. arundinacea* | *F. rubra* | .457 | .000 |
| | *P. pratensis* | .751 | .000 |
| *F. rubra* | *P. pratensis* | .294 | .000 |
| | | | |
| **Significant Post hoc Results for** Street Dust **Treatment with Non-Bent Grasses** | | | |
| Street Dust (I) | Street Dust (J) | Mean Difference (I-J) | Sig. |
| 40g Street Dust | Control | .240 | .017 |
| | 5g Street Dust | .264 | .009 |
| 20g Street Dust | 5g Street Dust | .213 | .032 |

The Bents (*A. capillaris syn.tenuis*, *A. stolonifera and A. canina)* showed no difference in biomass, both between the three species and with different street dust treatments. However, the non-bent grasses produced significant results for grass species with the post hoc tests indicating that *L. perenne* and *F. arundinacea* produced similar quantities of biomass which was significantly higher than *F. rubra* and *P. pratensis*. The post hoc tests of street dust treatments also suggested that for the non-bent grasses the 20g and 40g treatment produced more biomass than the control.

## 4.7 The pH Analysis

The pH of the compost can influence the availability of nutrients for plants and therefore the amount that would be accumulated (Taiz and Zeiger 2006:83). Decreasing pH in soil has been shown to increase the availability and accumulation of heavy metals by grass, with an increasing pH having the opposite affect (Deletic, 2005). Typically the majority of nutrients are more available in the pH range of 5.5 to 6.5 (Taiz and Zeiger 2006:83). Although the trial lacked conditions such as acidic rainfall that would alter the overall pH of the compost, street dust originates from urban surfaces and includes particles from de-icing agents or building materials that would increase its alkalinity and therefore reduce the accumulation of heavy metals by the grasses. However the median pH values (Figure 4.7) indicate that there is only a small variation. The variance bars show this by illustrating the maximum and minimum values on Figure 4.7. In the environment, factors such as anaerobic conditions would also influence the pH, producing carbonic acid to lower the pH (Killham 1994:25).

***Figure 4.7: Median pH for Control, 20g and 40g Street Dust Treatments***

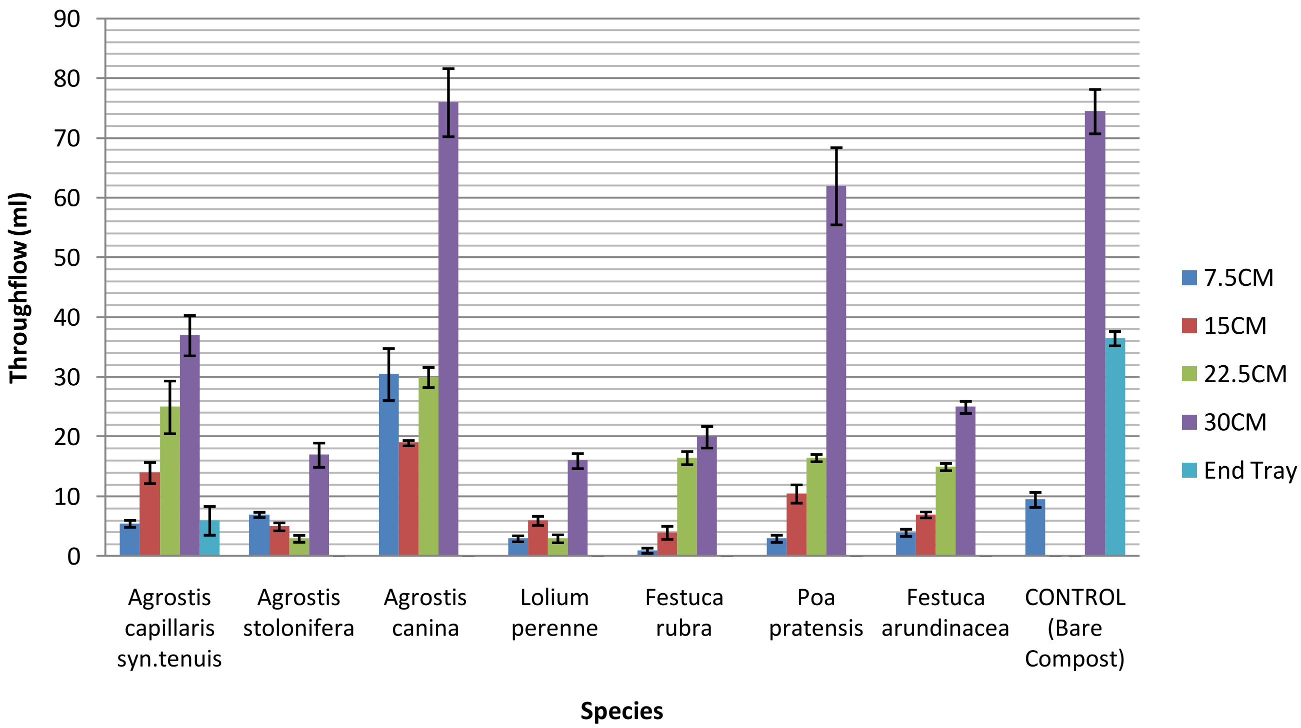


## 4.8 - Hydraulic Retention Tests

A vital part of a vegetated SUDS mandate is to either channel excess runoff to other SUDS or to reduce the volume of the flow by infiltration. Deletic (2001:169) suggested that characteristics such as denseness and thickness of blades would have an impact on the performance of a vegetated surface. There are also thought to be more important controlling factors such as the infiltration rate, saturation, volume and velocity of runoff that influence and dictate hydraulic performance (EPA, 1999:3; Latin and Barrett, 2005:6; Johnson et al. 2003). With two different densities of grass were sown (Bents sown at $20gm^2$ and non-bents sown at $35gm^2$), this trial would provide information to answer the second research objective (See Section 2.6) as well as inform a recommendation for the suitable species.

Figure 4.8 shows the mean results of the hydraulic retention tests, which shows no link between species and the total amount of collected throughflow. However, the Bents, in particular *A. canina*, do show the highest amounts of recorded throughflow. All the species have more collected throughflow in the central sections of the tray than the bare compost control, indicating that they are encouraging more infiltration rather than the control which only registered significant amounts of infiltration at the 30cm collection point. This indicates that the simulated runoff simply flowed over the top of the compost, pooling at the end of the control tray. The grasses provided resistance to the flow encouraging infiltration; however the trial only shows a limited amount about the hydraulic performance of the different grass species in relation to each other.

***Figure 4.8****: Hydraulic Retention Test Results with 400ml Stimulated Runoff*




Two-way ANOVA analysis (species and distance along the tray as factors) was conducted in two groups based on the densities they were sown, Bent grasses (*A. capillaris syn.tenuis*, *A. stolonifera* and *A. canina*) and non-bent grasses (*L. perenne*, *F. rubra*, *P. pratensis* and *F. arundinacea*). Both the Bents and the non-bent species showed no significant difference in the amount of water that was collected along the trays with differing species. From the amount of throughflow collected along the distance of the tray only the non-bent grasses showed a significant difference (sig. =0.04). Post hoc analysis indicated that throughflow collected at 30cm was significantly more than all the other collection points. However, as the length of the trial trays were small it was not possible to make exact comparisons. More importantly it shows that for this trial, the grass used did not affect the collected throughflow and therefore infiltration. The presence of the grass clearly encouraged infiltration with a larger amount of throughflow being collected in the middle sections of the tray than for the control. The Bents in particular seem to be effective at encouraging infiltration.

## 4.9 Overview of Results

Initial analysis focussed on determining whether street dust would be a suitable simulated pollutant. Analysis of the street dust and John Innes compost showed their geochemical variability; the street dust having much higher yet variable concentrations of heavy metals. The John Innes compost had little variation in heavy metal concentrations between samples which was related to the fact that the compost is made to official standards and the street dust is not from one fixed source. Heavy metal extractable tests showed the street dust and compost leached similar concentrations of heavy metals except for Ni which was much higher in street dust. Pollutant retention tests showed that the street dust treatments did not have a significant effect on the concentrations of the middle layer (B) in the pots; higher concentrations were found in the upper most layer (A) of the compost core with smaller concentrations found in the lower layers for the majority of species. However, post hoc tests showed that *P. pratensis* and *A. capillaris syn.tenuis* had the highest concentrations of heavy metals in Layer C. Whilst different layer showed different concentrations, mineral magnetic analysis showed that the street dust mainly remained in Layer A.

As well as examining the compost, the distribution of heavy metals in the pollutant retention trial involved analysis of the grass roots and shoots. The root analysis showed no statistical significant differences for heavy metal concentration with street dust treatment although there were significant differences with different grasses reflecting differing ability to uptake metals. Two-way ANOVA analysis results for street dust showed that Cu and Zn were close to being significant (0.069 & 0.120 respectively); one-way ANOVA analysis was therefore conducted on all the species for these metals. However, the only significant results from one-way ANOVA analysis was for Cu in *A. capillaris syn.tenuis* and Cd for *A. canina*. Using the post hoc analysis from the original two-way ANOVA on the roots showed that Bent grasses seem particularly affective at taking up heavy metals and had the highest concentration in the roots. Pb seemed to have a statistically similar uptake for all the grass species.

Analysis of shoots showed that there were significant differences between grass species as well as street dust treatments. However, with an interaction between street dust and species no clear determination could be made as to which factor caused differences. From reviewing the results, *A. canina* was determined to be responsible for much of the interaction and was removed, with two-way ANOVA analysis then being performed again. This showed that Cu and Pb were significantly different with street dust treatment with post hoc analysis showing that the larger treatments (20g and 40g) were producing concentrations in the shoot significantly different to that of the lesser treatments (control, 5g and 10g). The heavy metals that showed significant differences with species remained the same with *A. capillaris syn.tenuis* being shown to consistently have higher concentration of Cu, Ni and Zn than the other species. *P. pratensis* appeared to accumulate higher concentrations of Cu and Zn than the remainder of the species. Separate one-way ANOVA analysis of the heavy metal concentrations showed that Cu, Ni and Zn in *A. canina* was mainly significantly different in comparison with other species with the street dust treatments, although for Pb *A. canina* tended to be significantly different to the other species for the 10g and 20g treatments. *A. capillaris syn.tenuis* and *P. pratensis* showed the only other significant difference with each individual street dust treatment with the former showing potential for accumulation of Ni and Zn whilst the latter only showed significantly higher concentrations to species other than *A. capillaris syn.tenuis* and *A. canina* in the 20g street dust treatment for Cu, Pb and Zn. The compost pH was found to show little variation between species and with respect to the control. It is also slightly alkaline, being above the 5.5-6.5 which is optimal for heavy metal availability (Taiz and Zeiger 2006:83)

The biomass was analysed in groups determined by their sown density and showed no significant differences with different street dust treatments for the Bents, suggesting that street dust application produced no noticeable changes in growth compared to the control and that all species were capable of growing normally with it present. However, the non-bent grasses showed significant differences with both grass species and street dust. In particular the 20g and 40g street dust treatment showed increases in biomass.

Hydraulic testing revealed that there was no significant difference between species and throughflow along the sample trays. However, there was a significant change with the recorded throughflow along the length of tray for the non-bent grass indicating that length of the tray was influential on throughflow results. The lack of significance between species indicates that there are more dominant factors affecting hydraulic performance than the grass species. However, the Bents did produce the greatest throughflow indicating that they have potential for encouraging infiltration.

The next chapter uses these results to answer the research question that was posed in Chapter 2. The information on distribution of heavy metals in the compost, roots and shoots as well as hydraulic performance will be placed into a context regarding a practical use. This will cumulate in providing recommendations of grass species that might be suitable for vegetative SUDS devices as well as suggestions for further study.

# 5.0 Discussion

In the previous chapter the results of a series of trials were given to determine the pollutant and hydraulic retention capabilities of seven grasses. These characteristics were investigated in order to give an indication of their potential for heavy metal removal and ability to retain runoff and hence, to make recommendations of grasses or mixtures of grasses that would perform most effectively when planted in a vegetated surface.

This chapter aims to use the results to address the aim and objectives detailed in Chapter 2. As well as taking the results into consideration, it also examines other key aspects of the grasses to determine whether they have other characteristics that may be beneficial. Reflections on the validity of the methods will also be discussed along with suggestions for further study.

## 5.1 Analysis of Street Dust Heavy Metal Concentrations

Initially, analysis focused on the street dust to determine heavy metal concentration. Street dust was chosen with the issues behind collecting and preparation discussed previously (See Section 3.2). Analysed samples of the street dust (Table 4.1), showed large variations in Cu, Pb and Zn. With no single source, it is likely that there would be differences in heavy metal concentrations between samples due to the human activities present in each area (Wong et al. 2006:5). For example, if samples were taken from a busy main road there might be elevated concentrations of Cu and Zn which are associated with tyre and brake wear compared to that of a quiet suburban road (Patel, 2005:137). Cd and Ni were found in small quantities in the street dust, reflecting their scarceness naturally (Wild, 1993). Variations were also found with different particle sizes, supporting Zander's (2005:44-45) study, which found that particles <250µm had higher heavy metal concentrations. The concentrations of different particle sizes were investigated briefly in section 3.2.1, which found that smaller particles had larger standard deviation and therefore larger ranges of concentrations (See Table 3.2).

| *Table 5.1: Comparison between street dust studies in the UK and around the World* | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | **Concentration (mg/kg)** | | | | |
| Author | Subject | | Cd | Cu | Ni | Pb | Zn |
| EA, 2003 | Background topsoil in England and Wales from 1980-1995 | | 0.62 | 25.8 | 33.7 | 29.2 | 59.8 |
| Zander (2005) | Road sediment characterisation, New Zealand | | - | 181-212 | - | 251-334 | 1073-2080 |
| De Miguel et al (2007) | Risk analysis of street dust, Madrid, Spain | | 0.19 | 20 | - | 38 | 78 |
| Elik (2003) | Street dust analysis in Sivas, Turkey | | 2.6 | 84 | 68 | 197 | 208 |
| Baptista & Miguel (2005) | Risk analysis of Street dust in Luanda, Angola | | 1.1 | 42 | 10 | 351 | 317 |
| Brown & Peake (2006) | Study of heavy metal sources in urban areas – Street Dust (New Zealand) | | - | 129 | - | 289 | 528 µg/g |
| Wilson et al (2003) | Performance of pervious pavement after street dust addition | | 0.9 | 170 | - | 130 | 630 |
| Charlesworth et al (2003) | Conc. & distribution of street dust, Coventry & Birmingham, UK | B'ham | 1.6 | 466.9 | 41.1 | 48.0 | 534 |
| | | Cov | 0.9 | 226.4 | 129.7 | 47.1 | 385.7 |
| This Study (Table 4.1) | Coventry Street Dust (Average Concentration) | | 1.55 | 185.91 | 17.90 | 66.88 | 314.59 |

In order to evaluate this study, it was essential to compare it to a similar study based in Coventry (Charlesworth et al. 2003). This study produced similar concentrations of Cu, Pb and Zn however, there were difference of around 20-40mg/kg for each of the heavy metals but this may be attributed to the spatial variation between the collection of samples by Charlesworth et al. (2003) and this study. Spatial variations are also illustrated by other studies, which show variations in Cu, Pb and Zn (Table 5.1). Another explanation could be that particles high in particular heavy metals (for example, part of a battery which would be high in Ni) can become trapped with other materials forming an accumulation of particles which if sampled may skew the concentration. This reasoning could be attributed to the difference in Cd and Ni results. However, as this study exhibited similar results to Charlesworth et al. (2003) it is suggested that the street dust collected was representative and a suitable simulated urban pollutant.

There were a few issues regarding the street dust and heavy metal variations highlighted in previous chapters. With large variations it was difficult to determine whether the concentration of the material placed onto the pots for the pollutant retention trial affected the compost concentrations in the different layers. Large variations also made it difficult to assess the effects of the street dust on grass species, particularly the concentrations of heavy metals in the roots and shoots. The error bars on Figures 4.1, 4.4 and 4.5 illustrate the large scale of variation in street dust treatments. As lesser treatments produced concentrations higher than larger street dust treatments it could be argued there was a lack of consistency between the treatments in regard to heavy metal concentrations. If repeated, street dust would be collected from a narrower range of sites and then street dust samples chosen from sites with similar concentrations of heavy metals. This would possibly give a less variable set of samples although would also be less representative of Coventry as a whole. However, even this may still produce variability as no one site would be the same. Alternatively a more extensive program of testing to determine the suitability of the street dust could be established to test longer homogenisation procedures. Different methods of representing the heavy metal concentrations of the street dust could also be trialled to give a more accurate impression of the effects of heavy metal concentrations on the grass species.

## 5.2 Analysis of Heavy Metal Concentrations in the Compost of Pollutant Retention Trial

The first objective of this study was to determine the distribution of heavy metals not just in the shoots and roots but also in the compost. The compost was one particular area where heavy metals could accumulate. Similarities were found in comparison with a study focussing on roadside soils and grasses in Gipuzkoa, Spain by Garcia and Millian (1998). Focussing on Cu, Pb and Zn in soil samples, Cu concentrations were found to be similar in the compost to soil samples taken by Garcia and Millian (1998) although Pb and Zn differed significantly. For Pb the majority of concentrations in this study were between 30-40mg/kg, whereas in Spain some of the soil samples had much higher concentrations; particularly samples collected from main roads (Pb concentrations of 100+mg/kg). On the other hand, Zn concentrations in compost in this study were higher than those found by Garcia and Millian (1998) with their samples being approximately 10-40mg/kg compared to the majority of samples in this study being approximately 40-50mg/kg. Increased Zn and decreased Pb could be linked to factors of intense human activities with higher Pb being found on main roads and prone to more deposition by motor vehicles. This is illustrated by the variability in street dust between samples in this study.

Although the results are similar to Garcia and Millian (1998), in order to have a valid point of comparison the Inter-Departmental Committee on the Redevelopment of Contaminated Land threshold values (ICRCL – 1983 – See Table 5.2) and the more recent Contaminated Land Exposure Assessment (CLEA) soil guideline values for contaminated land (See Table 5.2) were used. These values provide threshold concentrations below which no action is needed whereas concentrations above this threshold require immediate attention (Charlesworth et al. 2003:568; Thomas, 2005:460; Environment Agency n.d.).

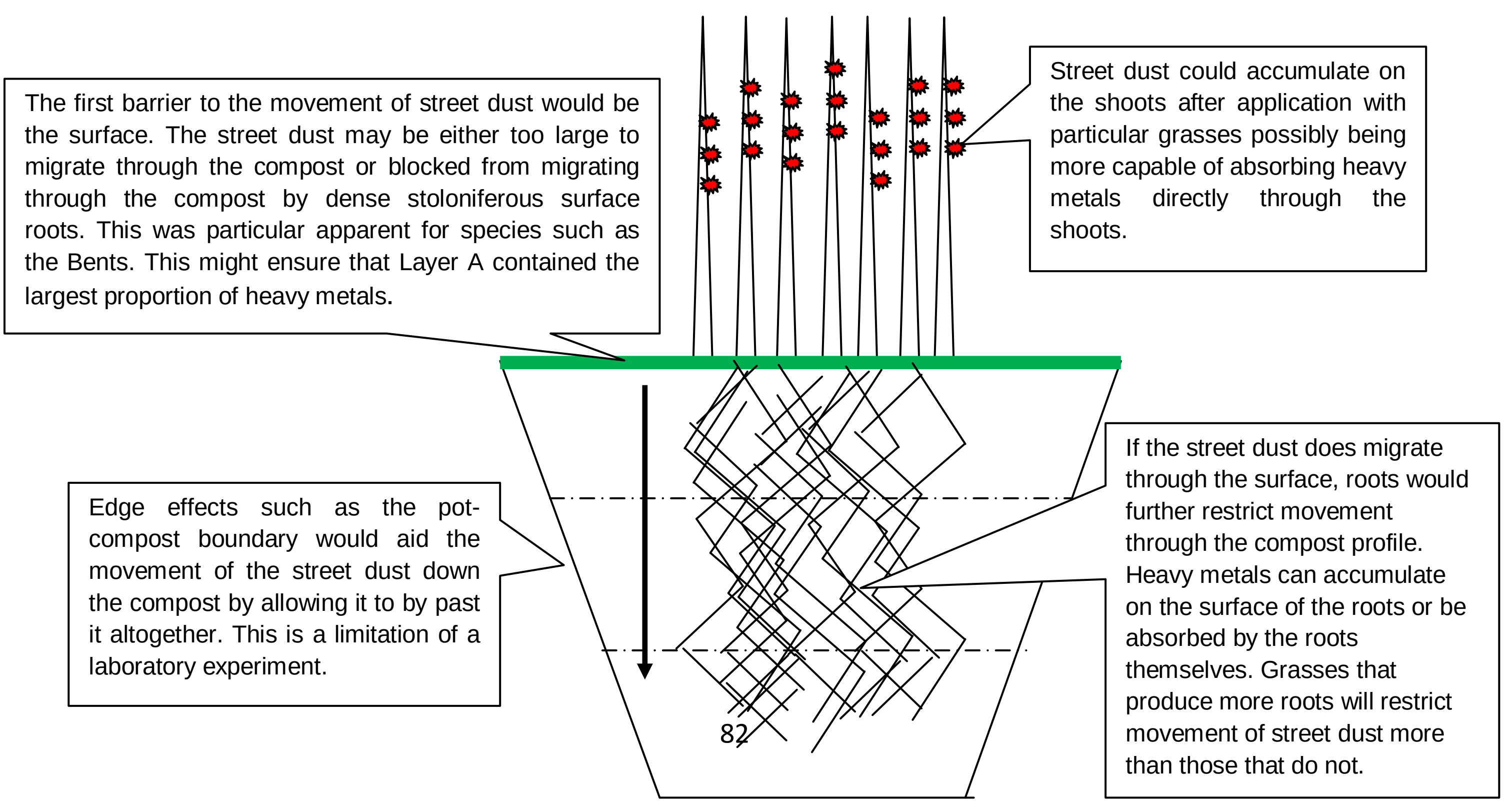
***Table 5.2:*** *Published Soil "Trigger Concentrations"*

| Contaminant | Planned Use | Trigger Concentrations (mg $kg^{-1}$ air-dried soil) Threshold / Action | CLEA Values (mg $kg^{-1}$ air-dried soil) |
|---|---|---|---|
| Cadmium | - Domestic Gardens, Allotments<br>- Parks, playing fields, open spaces | 3 / 15<br>15 | 30 |
| Copper | - Anywhere where plants are grown | 50 | ND |
| Nickel | - Anywhere where plants are grown | 70 / 376 | 210 |
| Lead | - Domestic Gardens, Allotments<br>- Parks, playing fields, open spaces | 500 / 813<br>2000 | 450 |
| Zinc | - Anywhere where plants are grown | 130 | ND |
| Source: Charlesworth et al. 2003:568; Thomas, 2005:460; | | | |

.

Of the Layer B compost results, the standard error bars show that *A. capillaris syn.tenuis*, *L. perenne*, *F. rubra* and the control exceed their threshold concentrations (see Figure 4.1). Figure 4.2 also shows that Layer A and sometimes Layer C, had values that trigger these thresholds for Cu and Zn. This was exacerbated by the samples being collected from pots which received the largest treatment (40g street dust) making it more likely that they would have values that would exceed the trigger values than smaller treatments. ANOVA post hoc analysis (Table 4.5) showed that for each species the highest concentrations for most samples were in Layer A. Only *P. pratensis* and *A. capillaris syn.tenuis* had heavy metal concentrations higher in Layer C. One possible reason for Layer A having the highest concentrations was that this was where the street dust was directly applied, indicating that it remained mainly in the upper layer (A). This was reinforced by mineral magnetism, which showed that all the species showed Layer A to have the highest susceptibility readings of all the Layers. However, susceptibility analysis only shows a distribution of the magnetic particles in the street dust, so non magnetic particles (e.g. material worn off tyres) was not displayed. Figure 5.1 illustrates the possible barriers to street dust movement in the pots. High concentrations in Layer A would be mainly down to the street dust being too large to migrate through the compost profile. Also dense root structures on the surface and in Layer A would further restrict street dust from moving into the compost and thus remain on the surface. If the majority of street dust remains on the surface there is an issue that it could be re-suspended with later runoff events (Escarameia et al. 2006:11). To avoid this, routine maintenance such as removal and disposal of build ups of sediments would be necessary, for example spiking topsoil to improve infiltration and preventing compaction of the soil would be critical in preventing street dust being re-released (Wood-Ballard et al. 2007:262).

***Figure 5.1**: Considerations Regarding the Movement of Street Dust*



It was found that different species did not show significant differences for any of the heavy metals but may have individually accumulated different metals in varying quantities (Figure 4.1). Heavy metals in the compost did not show significant difference with street dust treatments in Layer B, therefore any changes in concentrations may represent the grasses removing heavy metals from the compost rather than concentrations being influenced by the presence of street dust. The compost sampled from certain species such as *A. canina* and to some extent *P. pratensis* showed (see Figure 4.1) lower concentrations of all heavy metals suggesting that the plants may have taken up larger quantities of heavy metals from the compost than the other species. Applying this idea to concentrations in the different layers (Figure 4.2) it suggests that all the species except *A. capillaris syn.tenuis* and *P. pratensis* have root systems developed mainly in the lower layers (B & C), therefore transporting more of heavy metals from those areas (Table 4.4 and 4.5). With these species having fewer roots in Layer A, a smaller amount of soluble heavy metals would be accumulated therefore giving it higher concentrations compared to the other layers. *A. capillaris syn.tenuis* and *P. pratensis* illustrated the opposite with the post hoc tests (Table 4.5) showing that they have their largest concentrations in Layer C. This shows stoloniferous root systems that are more developed in Layer A and B therefore retaining and allowing accumulation of larger quantities of soluble heavy metals from these layers, leaving Layer C to have the higher concentrations in comparison to the other Layers. This is particularly important as the Bents and *P. pratensis* are known to have stoloniferous roots or rhizomes that would form on or near the surface (DLF Trifolium n.d.). However, stoloniferous roots may also act as a barrier to the movement of street dust trapping it on the surface as explained in Figure 5.1. This was illustrated in Layers A and C which had similar concentrations of Zn for *A. canina*, suggesting that the presence of stoloniferous roots might help uptake and therefore the removal of heavy metals from the surface (Layer A). However, the addition of street dust to the pot increased the concentration of heavy metals in Layer A to a point where there was no significant difference between Layers A and C. From a practical perspective using a combination of grasses that combines root structures on the surface and those which penetrate into the lower layers of compost would allow for effective removal of the soluble heavy metals within street dust. However, with the street dust mainly remaining on the surface, species such as the Bents and *P. pratensis* may be more suitable if accumulation of heavy metals is the main aim with their stoloniferous roots. Re-suspension of street dust is another issue that could be limited by the selection of grasses with less dense root systems which would allow less restricted movement of the street dust. This would allow more street dust to become trapped in the compost and therefore reduce the amount available for re-suspension.

Mineral magnetism allowed for further detection of the presence of magnetic particles in the street dust and their distribution in the compost profile. Low frequency susceptibility was measured and produced an average value of 3.86 $10^{-6}m^3kg^{-1}$. This is similar to other studies conducted by Xie et al. (2001) and Shilton et al. (2005) who investigated street dust in Liverpool. This is also within the range of street dust values found by Charlesworth and Lee (1997 & 2001) that was conducted in Coventry, showing that the street dust sample was representative as it could be within the displayed variability of the constitutes of street dust.. When comparing the susceptibility of various treatments (Figure 4.3) the 40g street dust treatment produced susceptibility values similar to that of the street dust sampled separately, with decreasing susceptibility with decreasing size of treatment. This is logical as with smaller amounts of street dust there would be a smaller susceptibility. Some of the street dust does seem to migrate down profile with Layer B and C susceptibility readings being slightly higher than the 0.13 $10^{-6}m^3kg^{-1}$ background that was measured for just compost. The finer street dust that would have the capability of migrating through the compost was shown by Zander (2005) to have higher heavy metal concentrations than larger particles. Zander (2005) characterised street dust in New Zealand and of the total metal concentration, particles <125µm contained 43% Cu, 54% Pb and 36% Zn. From a SUDS performance perspective if the finer minerals are trapped, migrate into the compost to be retained and are not capable of being re-suspended, there will be an improvement in the quality of runoff leaving the vegetated SUDS. However, if only the finer street dust is migrating down into the compost with the rest trapped in the upper layer (A) the street dust is prone to re-suspension (Deletic and Fletcher, 2006). Soil is particularly important for street dust removal; Sun and Davis (2007:1608) found that 88-97% of heavy metals are captured by the soil medium. However, removal is also attributed to the design characteristics of the vegetated SUDS itself, something that will be explained in more detail further on in the Chapter.

Overall, street dust was shown not to effect the concentrations of heavy metals in Layer B significantly although this does not mean that it would not affect the concentrations of Layer A significantly as this was where the street dust was applied. By concentrating on Layer B and less so on the other two layers the presence of the street dust throughout the whole core may not have been fully recorded as only small amounts migrated down the compost profile. More extensive sampling of Layer A might have shown not just a difference between the layers but also between the street dust treatments. The mineral magnetism showed that the finer material was possibly migrating to the bottom of the pot via the sides, the roots were still being subjected to the street dust and therefore could have had an effect on the concentrations of heavy metals in the shoots. Examining the concentrations of heavy metals in the roots and shoots was necessary in order to answer the first research objective and establish the distribution of heavy metals in the pots after street dust application.

## 5.3 Analysis of Root & Shoot Heavy Metal Concentrations

Shoot and root heavy metal concentrations were then examined (See Figure 4.4 & 4.5) to determine the distribution of heavy metals in the grasses and also to provide recommendations of suitable grasses for vegetative SUDS. The results illustrated how the different species responded to the addition of street dust with increased concentrations in the roots and shoots showing a positive effect on the accumulation of the heavy metals. Kalis et al (2007) stated that concentrations of heavy metals in the compost could relate to the concentrations in the roots. With the street dust not significantly affecting heavy metal concentrations in Layer B, a decrease in compost heavy metals showed natural accumulation from the compost by the different grass species. Therefore the lower the concentration of heavy metals in the compost, the larger the possible uptake into the roots and shoots. With street dust's limited migration shown by the magnetic susceptibility results (Figure 4.3), species with roots that develop nearer to the surface as opposed to roots growing mainly in the lower layers (B & C) might show evidence of accumulating heavy metals that were soluble. The compost concentrations (Figure 4.1) and summary of significant post hoc results (Table 4.5) showed that *A. canina*, *P. pratensis* and to some degree *F. rubra* had the lowest concentrations in Layer B. This corresponds with the roots which showed that *A. canina* generally had one of the highest concentrations for each of the metals, indicating larger uptake from the compost. Unfortunately, *P. pratensis* was not tested due to a laboratory accident which resulted in the loss of all root material. This is unfortunate as the rhizome root systems which would have developed in the upper layers of the compost would have been subjected to direct application of the street dust and therefore more likely to remove soluble heavy metals (DLF Trifolium, n.d.).

All the heavy metals showed significant difference in concentrations with different species but not with street dust treatment (Table 4.7). Figure 4.4 shows that there is a large amount of variation in heavy metal concentrations which might have influenced the ANOVA analysis as smaller treatments could display similar heavy metal concentration to larger treatments therefore resulting in ANOVA finding no significant difference between treatments. However, individual analysis of the species (Table 4.8) suggested significant differences with Cd for *A. canina* and Cu for *A. capillaris syn.tenuis*. This illustrates two things; either the heavy metals in the street dust lacked mobility or street dust did have significant effect on the uptake of heavy metals but at the time of sampling the heavy metals had already translocated to the shoots. The lack of mobility of heavy metals in street dust is feasible and most likely which is supported by Pitt et al. (1999:227) who suggested that heavy metals are generally not very mobile especially when attached to particulates. Also the compost pH is slightly alkaline compared to the optimum 5.5-6.5 for heavy metal availability (Taiz and Zeiger 2006:83). This would mean that the majority of the heavy metals were unobtainable to the plants as they would be bound to insoluble particles. Extractable heavy metals shown in Table 4.2 displays results that concur with Pitt et al. (1999); although only Ni was leached out of the street dust in significant quantities when mixed with de-ionised water. Therefore the available heavy metals attached to the street dust which was applied to the compost may not have been sufficient to provide enough heavy metals to cause a difference in the roots with different street dust treatments. Also, Table 4.5 suggested that perhaps some of the species had root systems that were mainly distributed in the lower layers of the compost (B and C) with minimal surface roots which would reduce access to the soluble heavy metals in the street dust. *P. pratensis*, *A. capillaris syn.tenuis*, *A. stolonifera* and *A. canina* showed either evidence of, or have been documented to have, stoloniferous root structures or rhizomes that would be situated on or near the surface aiding the up-take of available metals from the street dust (See Figure 5.1) (DLF Trifolium n.d.). *A. stolonifera* in particular has highly stoloniferous roots and illustrates the possible advantage of having roots developed close to the surface, resulting in it having the highest root concentrations (Table 4.9) (Bond et al. 2007). However, like *A. canina*, *A. stolonifera* did not show that Layer C was significantly different to the other layers as might be expected if it was removing heavy metals from Layer A and B (Table 4.5). As section 5.2 explained, the addition of street dust to the surface may have been masking the differences between the compost layers caused by the roots of the different species accumulating heavy metals from particular layers of the compost. The roots would also trap the street dust in the upper layers making it difficult to determine whether the street dust was affecting the roots in the lower sections of the pot. However, as *A. stolonifera* and *A. canina* had some of the highest metal concentrations in the roots (Table 4.9) it can be deduced that their stoloniferous root structures may have helped to increase heavy metal accumulation in the roots. *A. capillaris syn.tenuis* also had high accumulations of Zn in the roots, another example of a species with roots that develop near the surface which could be more successful at accumulating heavy metals from street dust.

The shoot concentrations (Figure 4.5) showed that *A. canina* had the largest concentrations of all heavy metals in the shoots by far, showing that the accumulation of heavy metals from the compost via the roots resulted in heavy metals being transported to the shoots. Figure 4.5 showed that Cu, Pb and Zn were affected by street dust treatments with these heavy metals having significant differences with the street dust treatments (Table 4.11 & Table 4.14); in particular the 20g and 40g street dust treatments (Table 4.12). The differences caused by the larger treatments does reinforce the hypothesis that a large quantity of street dust would be required to make significant differences due to the lack of mobility of heavy metals in the street dust. This lack of mobility was illustrated by the water extractable experiment (See Table 4.2). Also as the pH was slightly alkaline, opposed to the optimum 5.5 - 6.5 for metal availability which would restrict the quantity that the plants could accumulate, a larger amount of street dust would be required to make an impact (Taiz and Zieger: 2006:83). But some species had high metal concentrations in their shoots e.g. *A canina and A. capillaris syn.tenuis* which appeared to have accumulated Ni. This possibly relates to the much higher extractability of Ni demonstrated in Table 4.2. Shoot concentrations also corresponded with the earlier hypothesis that the decreased concentrations in Layer B are a result of increased uptake by the grasses with *A. canina* having significantly higher Cu, Ni and Zn concentrations. *P. pratensis* and *A. capillaris syn.tenuis* also displayed this trend resulting in significant accumulation of Zn in the shoots. Therefore Bents (in particular *A. canina* and *A. capillaris syn.tenuis*) and *P. pratensis* demonstrate a pattern of accumulation of heavy metals compared to the other species. As *A. canina*, *P. pratensis* and *A. capillaris syn.tenuis* accumulate heavy metals in their shoots, maintenance practices such as mowing would remove the parts with the highest concentrations of heavy metals. Also *A. canina*, *A. capillaris syn.tenuis* and *P. pratensis* showed that with each street dust treatment they outperformed the other species consistently (Table 4.16). This is not necessarily positive as accumulations in the shoots would mean that grass cuttings needing to be disposed of in a safe way. Although *A. canina* seemed be most successful at the accumulation of all heavy metals, *A. capillaris syn.tenuis* showed potential for taking up Ni and *P. pratensis* for Cu and Pb. A possible reason for *A. canina* having such high concentrations could be related to accumulations through the shoots as shown in Figure 5.1. Heavy metals in the environment could either be taken up from the soil or deposited on the shoots directly from atmospheric sources (Alloway, 1995:26). However, the primary point of accumulation is through the roots rather than the shoots (Kurdziel et al. 2004:167). Leaves can take up both essential and non essential heavy metals which are absorbed to different degrees depending on the heavy metal involved (Kurdziel et al. 2004: 9). More importantly variations in accumulation of heavy metals through the shoots can depend upon the species and their shoot characteristics. Environmental stresses effect this accumulation as it would with heavy metals accumulated by the roots. Changes in pH which could be caused by acid rain could cause increases in accumulation. Also toxic accumulations through the roots have been shown to increase heavy metal accumulation through the shoots. An example used by Kurdziel et al. (2004:10) is that Cd uptake by the roots can cause higher permeability in the shoots increasing accumulation through this pathway. With species known to show variation in the amount accumulated through the shoots, analysis of the characteristics of *A. canina* was needed to determine whether it had characteristics that make it different from the other species and more suitable for accumulating heavy metals through its shoots rather than just through the roots. Clayton et al. (2008) described *A. canina* as having a rough ribbed surface that would help capture heavy metals on the shoots, especially with the street dust was applied from above. The other Bents (*A. capillaris syn.tenuis* and *A. stolonifera*) demonstrate similar textured leaf characteristics, however, the results of the shoots do not show such drastic heavy metal accumulation (See Figure 4.5). Other species such as *L. perenne* have smoother textured shoot which would not capture the applied street dust as effectively as *A. canina* and therefore limit the amount of heavy metals accumulated in this way. However, the concentrations of heavy metals in the roots or shoots of heavy metals are significantly larger for the majority of species with the 20g & 40g treatments compared to the smaller treatments (5g and 10g) suggesting that *A. canina* accumulates more heavy metals regardless of the mechanism used.

Heavy metal concentrations in the shoots and roots also followed similar patterns to those described by Kalis et al (2007) which adapted a stepped approach to explain heavy metal accumulation by *L. perenne*. Kalis et al (2007) showed that Zn shoot concentration increased linearly with concentrations in the roots. Cd, Cu and Pb shoot concentrations were described as being related to the roots (reaching a maximum concentration before the metals were transported to the shoots). It was found that Cd, Cu and Pb exhibited higher concentrations in the roots than in shoots, although *A. capillaris syn.tenuis*, *A. canina* and *P. pratensis* appear to have similar concentrations in both components. Concentrations of Cd were too small to show a significant difference between shoot and root concentrations (See Figure 4.4 & 4.5). Zn increased in concentration with increased street dust application which was similar to the linear increases described by Kalis et al (2007), with significant increases in concentration with street dust treatment in the shoots but not roots. This could be explained by the large amount of variation seen with not just Zn but all the heavy metals. The variation of the heavy metal concentration in the roots can possibly be attributed to material on the outside of the root that was not cleared off with the cleaning process. In that case the root concentration would not just represent concentrations accumulated in the roots but also some of the material from the outside. Ni shoot concentrations were more difficult to describe as there were extremely high mean concentrations (majority >1000+ mg/kg) for *A. capillaris syn.tenuis* and *A. canina*, though this was not exhibited in the roots where concentrations mainly varied between 5-9mg/kg. Ni was the more mobile element as its highest concentration was in Layer C of the control (Table 4.5) therefore indicating that it might be more easily accumulated in Layer A for species such as the Bents which have stoloniferous roots that would be present to uptake soluble heavy metals. As *A. capillaris syn.tenuis* and *A. canina* showed high concentrations of Ni in the shoots, they are effective at accumulating Ni from the compost, although this could be a direct process of accumulation through the shoot surface as explained previously. Bents have been known to have a robust capacity to tolerate heavy metals such as Ni on contaminated mine sites (Monsanto Company and Scotts Company, 2003:17.; Shaw, 1989). Since Ni is more mobile this would allow all species to accumulate Ni readily from the street dust. Kalis et al. (2007) stated that pH could be an influential factor in shoot accumulation of Ni. The variation in pH (Figure 4.7) was small however, it was slightly alkaline therefore making metals more likely to be tightly bonded and therefore less available to plants.

### 5.3.1 Comparison of Root & Shoot Concentrations to Other Studies

The shoot concentrations of the pollutant retention trials show similarities to other studies that investigated uptake of heavy metals in urban areas (Table 5.3). Garcia and Millian (1998) studied roadside grasses on a selection of roads in Gipuzkoa, Spain showing similar Cd concentrations in grass tissue to those found in this trial. Other similarities included Cu and Pb concentrations for *A. canina*, *A. capillaris syn.tenuis* and *P. pratensis*, although the Zn concentrations in the Garcia and Millian (1998) study also have limited comparison with the species in this trial. However, concentrations on the main / local roads compared well with *A. stolonifera*, *L. perenne* as well as those from the higher street dust treatments (20g / 40g) for *F. rubra* and *F. arundinacea*. The “high road” concentrations of the Spanish study were comparable with *A. capillaris syn.tenuis*, *A. canina* and *P. pratensis*. Another investigation by Murray and Hendershot (2000) concentrated on testing the bioavailability of heavy metals from contaminated soils and showed largely similar results to the present study apart from a few differences. For example, Murray and Hendershot (2000) recorded much higher Cu concentrations than those in this study, with the exception of *A. canina*. Some Zn values reported by Murray and Hendershot (2000) were also much higher than anything found in this study. Due to the different grass species used, it is difficult to compare studies as the different grasses are capable of transferring varying amounts of heavy metals to the foliage. However, these studies showed that with similar concentrations meaning the type of vegetation may have a limited affect, particularly if the overall mobility of the heavy metals is low, something dependant on factors such as pH (Pitt et al., 1999:226-227).

| ***Table 5.3:*** *Other Studies Heavy Metal Concentration in Plant Shoot Tissue* | | | | | | |
|---|---|---|---|---|---|---|
| Author | | Concentration in Grass Tissue (mg/kg) | | | | |
| | | Cd | Cu | Ni | Pb | Zn |
| Garcia and Millian (1998) | Local Road | 0.14 | 11.94 | - | 4.15 | 31.90 |
| | Main Road | 0.11 | 10.07 | - | 3.47 | 32.34 |
| | High Road | 0.34 | 10.55 | - | 4.70 | 67.85 |
| Murray and Hendershot (2000) | | 0.665 | 30.171 | 3.892 | 4.404 | 74.892 |

## 5.3.2 Determination of the Degree of Toxicity of Root & Shoot Metal Concentrations

A further way to assess shoot metal concentrations was to determine whether the street dust had any negative effect on growth. Table 5.4 shows the results of this study compared to published levels that are deemed to be deficient, normal and toxic. All grasses have mean shoot concentrations of Ni which fall within the toxic limits for vegetation. However, the control frequently had similar concentrations of Ni to those of the various street dust treatments therefore making it difficult to assess their toxicity (Kabata-Pendias 2001:83). The high mobility of Ni, illustrated by its movement through the profile in the control (Table 4.5) and by its relatively high solubility as shown by the dissolution test (Table 4.2), would have contributed to making the Ni concentrations this high. Toxicity could cause problems with grass maintenance, as mowed cuttings need to be collected and transported off the site for safe disposal (Wilson et al. 2004:122; EPA, 1999:2-3). The only other grass species that had a mean heavy metal concentration in the shoots that was in the toxic range was *A. canina* for Cu. However as Table 5.4 shows *A. capillaris syn.tenuis*, *P. pratensis* and *A. canina* all had ranges that were at toxic levels for metals other than Ni. A number of deficiencies were also noted in the ranges for *A. stolonifera*, *L. perenne*, *F. rubra* and *F. arundinacea* for Cu and *A. capillaris syn.tenuis* and *F. rubra* for Zn. When comparing the levels in Table 5.4 with the average concentrations for each of the street dust treatments (Figure 4.5) only a small minority cause concentrations that are considered toxic. For example, *A. canina* had an overall mean concentration for Cu that was considered toxic yet only in the 10g and 40g treatments (Table 5.4) and had elevated concentrations for all heavy metals in the shoots (Figure 4.5). This illustrates a potential problem with the variation exhibited in the street dust with small amounts being capable of having large heavy metal concentrations. However, the majority of concentrations for Cd, Cu, Pb and Zn in all grasses are within normal limits as shown in Table 5.4.

***Table 5.4:*** *Comparison of Average Grass Shoot Concentrations and Natural Levels of Heavy Metal in Plants*

| | | Concentration in Shoots (mg/kg) | | | | |
|---|---|---|---|---|---|---|
| | | Cd | Cu | Ni | Pb | Zn |
| Kabata-Pendias (2001:83) | | -<br>0.05-0.2<br>5-30 | 2-5<br>5-30<br>30-100 | -<br>0.1-5<br>10-100 | -<br>5-10<br>30-300 | 10-20<br>27-150<br>150-400 |
| Hopkins and Hüner (2008:66) | | | <4<br>4-15<br>20+ | 0.05-5 | | 200+ |
| | | | | | | |
| Browntop Bent<br>(*A. capillaris syn.tenuis*) | Range<br>Mean | 0.06-5<br>0.91 | 1-94<br>15.57 | 0.61-8041<br>1610.64 | 0.45-17<br>3.97 | 7-125<br>74.27 |
| Creeping Bent<br>(*A. stolonifera*) | Range<br>Mean | 0.10-0.39<br>0.20 | 3-14<br>7.71 | 34-686<br>185.66 | 0.70-4<br>2.09 | 31-58<br>42.40 |
| Velvet Bent<br>(*A. canina*) | Range<br>Mean | 0.27-7<br>1.24 | 5-115<br>37.50 | 323-5446<br>2541.75 | 0.72-41<br>13.49 | 45-236<br>108.85 |
| Perennial Ryegrass<br>(*L. perenne*) | Range<br>Mean | 0.05-0.25<br>0.14 | 3-14<br>8.13 | 49-355<br>140.02 | 0.68-7<br>3.11 | 30-63<br>41.49 |
| Smooth Stalked Meadow Grass (*P. pratensis*) | Range<br>Mean | 0.09-218<br>8.91 | 6-47<br>17.73 | 39-256<br>91.19 | 0-11<br>5.01 | 26-106<br>59.95 |
| Strong Creeping Red Fescue<br>(*F. rubra*) | Range<br>Mean | 0.11-0.24<br>0.16 | 3-18<br>7.91 | 38.-143<br>84.05 | 0.37-5<br>2.15 | 17-42.<br>27.53 |
| Tall Fescue<br>(*F. arundinacea*) | Range<br>Mean | 0.17-0.40<br>0.32 | 0.89-6<br>3.48 | 44-120<br>70.54 | 0.53-3<br>1.69 | 22-40<br>30.17 |
| **KEY**<br>**Deficient / Normal / Toxic** | | | | | | |

## 5.3.3: Ranking of Species for Heavy Metal Accumulation Performance

With all the grasses showing overall mean concentrations within normal limits for the majority of heavy metals, their performance upon addition of street dust was determined by comparing the difference between average concentrations with the control (See Table 5.5). Other studies have used benchmarks to form selection criteria on the selection of SUDS (Ellis et al. 2004b). By using the average increase in concentration from the control a similar process could be applied to determine which grass species had the best performance. Using this method of ranking, *A. canina* and *P. pratensis* are the top performing grasses with *F. rubra* and *L. perenne* being ranked as joint third. This is realistic the former two species had significantly higher concentrations of metals on addition of street dust compared to the majority of the others (See Table 4.16) The post hoc summaries (Figure 4.9 and 4.16) showed a similar pattern with these grasses often in the top groups or grouped together. This ranking was given further credibility since *A. canina* and *P. pratensis* have consistently accumulated more metals than the other species in their shoots throughout the study. The difficulty with this method of ranking is that comparison with the control does not reflect the variability in results obtained, in that some of the smaller treatments produce larger differences in concentrations than larger treatments. Also the ranking would be affected by the variability in available heavy metals in the street dust, highlighted by the accumulation of heavy metals in the shoots of *A. capillaris syn.tenuis* which had one of highest sets of heavy metal concentrations according to the post hoc tests (Table 4.16) yet was ranked 6$^{th}$ using this method (See Table 5.5). However, there might have been little available heavy metals in the street dust to be accumulated in the shoots resulting in only small increases compared to the control, therefore causing it to be ranked lower. Accumulation in the shoots is not the only factor that might be important from a performance perspective. Although an accumulation in the shoots could allow heavy metals to be removed with maintenance (e.g. mowing) it could have negative connotations as it would act as a store for hazardous amounts of heavy metals. Mowed cuttings would need to be treated as hazardous waste and disposed of in a different manner to traditional green waste. This is an issue with regard to adopting of such devices as it would involve extra cost and management. Rather than metal uptake, maybe the use of grasses to simply slow runoff and allowing the suspend solids to become part of the soil could be of more importance. Grasses could be chosen to allow pollutants such as street dust to migrate through the soil whilst slowly accumulating nutrients in a manageable way. On the other hand, if heavy metals were an issue at a site, this ranking system would allow the choice of a grass that could accumulate as many heavy metals as possible to help in the removal of heavy metals from the site.

| ***Table 5.5**: Rank of Grasses based upon Shoot Concentration Differences from Controls* | | | | | | |
|---|---|---|---|---|---|---|
| | Shoot Conc. | | | | | |
| **Grass Type** | **Cd** | **Cu** | **Ni** | **Pb** | **Zn** | **Total** |
| *A. capillaris syn.tenuis* | - | 6 (J) | 7 | 4 (J) | 7 | 24 (6th) |
| *A. stolonifera* | - | 5 | 6 | 5 (J) | 5 (J) | 21 (5th) |
| *A. canina* | - | 1 | 1 | 1 | 1 | 4 (1st) |
| *L. perenne* | - | 4 | 5 | 3 | 3 | 15 (3rd) |
| *F. rubra* | - | 3 | 4 | 4 (J) | 4 | 15 (3rd) |
| *P. pratensis* | - | 2 | 2 | 2 | 2 | 8 (2nd) |
| *F. arundinacea* | - | 6 (J) | 3 | 5 (J) | 5 (J) | 19 (4th) |
| 1=highest average increase from control – 6 = lowest average increase from control<br>(J) = joint ranking | | | | | | |

Other factors such as physical characteristics and tolerance to factors such as inflitration rates are just as important for an effective grass species in a swale (Wood-Ballard et al 2007:262). Although *L. perenne* and *F. rubra* had a performance ranking lower than *A. canina* and *P. pratensis* it does not mean they are not suitable for vegetative surfaces. As Table 2.7 shows, *L. perenne* and *F. rubra* have qualities that allow them to establish themselves quickly and recover from wear effectively (Highways Agency, 2006). These are key qualities for vegetative surfaces which need to become established quickly to avoid incomplete vegetative cover. They also need to withstand and recover from the wear that runoff would cause avoiding the need for excessive maintenance and re-seeding. A key characteristic is also to be tolerant of saturated soils with swales frequently becoming inundated *A. canina* and *P. pratensis* show much slower establishment, growth rates and poorer recovery. Paired with grasses such as *L. perenne* and *F. rubra* which develop quickly, *A. canina* and *P. pratensis* can develop within established grasses and increase metal uptake from the deposited street dust (Highways Agency, 2006). Creating mixtures of grasses compensates for the disadvantages of a particular grass (DLF Trifolium n.d.).

## 5.4 Influence of Species & Street Dust on Dry Biomass Production

As part of the research aim, the biomass was weighed to examine the possibility that street dust affected shoot production. Street dust could have either a positive influence by supplying essential metals and organic matter to the grasses or a negative effect by providing too many metals and exceeding toxic concentrations (Kinnear and Gray, 2009:68). Overall the Bents produced the highest amount of biomass compared to the other grasses (See Figure 4.6). However, the difference in quantities of biomass produced could be related to the germination rates of the grasses, something that was not tested. Different germination rates would produce different quantities of shoots and hence different weights of biomass although it is more likely that the difference in biomass was due to the amount of seeds sown. The Bents (*A. capillaris syn.tenuis*, *A. stolonifera*, *A. canina*) containing approximately 1000+ seeds per 0.1g which is high in comparison to species whose seeds are larger (*L. perenne*, *F. rubra*, *P. pratensis* and *F. arundinacea*) which have approximately only a few hundred seeds per 0.1g (DLF Trifolium n.d.). Logically having more seeds will produce more shoots and therefore more biomass. Perhaps if this trial was conducted again a control seeding density could be constructed using the same method with duplicates. This would have been a better way of showing how each species compared to each other when exposed to the street dust treatments rather than individual controls at the two different densities. The Bents ANOVA illustrated that the street dust did not effect their growth, whereas non-bent species showed both significant differences with street dust and species with post hoc tests (Table 4.17) suggesting that *L. perenne* and *F. arundinacea* produced more biomass with the 20g and 40g street dust treatments which could aid in uptake (Sun and Davis, 2007:1608). This illustrates that although some of the species had concentrations deemed to be in excess for plants, there was no negative affect (See Table 5.2; Kabata-Pendias 2001). Biomass for *A. canina* increased for 10 10g and 40g street dust treatments which also had the highest metal concentration in the shoots. These two characteristics may therefore be linked since metals such as Zn and Cu are essential micronutrients used for a number of processes such as metabolic and oxidative reactions (Taiz and Zeiger, 2006:74-82; Hopkins and Hüner, 2008:73). It therefore seems reasonable to suggest that if these heavy metals were in sufficient quantities they could promote increased biomass production. However, if the concentrations of the micronutrients became too high, growth inhibition and a reduction in biomass occurs (Bonnet et al. 2000; Taiz and Zeiger, 2006: 83). There are also other nutrients that could be affecting biomass production which were not analysed such as nitrogen and phosphorous. Nitrogen is a constituent of many important molecules including proteins which stimulate growth of the shoot system (Hopkins and Hüner, 2008:69). Santibáñez et al. (2008:8) investigated biosolids noting greater biomass production for *L. perenne* mainly because of the increased availability of N to the grasses. Phosphorous is another important nutrient that in excess can promote growth in the roots and is therefore often used in fertilizers (Hopkins and Hüner, 2008:69). If these elements were present in the street dust they might have been responsible for the increased biomass production especially with the larger treatments possibly containing higher concentrations of N and P.

Increased biomass could prove beneficial for uptake of heavy metals with a laboratory based study on bio-retention systems by Sun and Davis (2007:1608) stating that increased biomass can potentially impact the accumulation of heavy metals. Overall the data for all the grass species shows that street dust had no ill effects making them suitable for use in vegetated SUDS. If this characteristic was considered. *L. perenne*, *F. rubra*, *P. pratensis* and *F. arundinacea* should be tested to determine whether they do have increased biomass production with street dust and whether this biomass increase relates significantly to heavy metal uptake.

## 5.5 – Hydraulic Performance

The second objective related to the hydraulic retention capabilities of the grasses. Vegetated surfaces such as swales, which are designed to convey and reduce runoff would benefit from having grasses that have superior hydraulic performance (Wood-Ballard et al. 2007:253). Good hydraulic performance would also be a basis on which to make recommendations of species which are suitable for such surfaces.

The hydraulic results compared well with Blanco-Canqui et al. (2004 – See Table 2.5) with the grasses encouraging more infiltration and throughflow than a bare compost surface. ANOVA analysis showed no significant differences between the grasses and throughflow collected along the length of the tray (See Table 4.18), the Bent grasses showed larger collections of throughflow in the centre of the trays indicating that they encouraged more infiltration. The non-bent grass species (*L. perenne*, *F. rubra*, *P. pratensis* and *F. arundinacea*) also showed significantly larger throughflow at the 30cm collection mark. The ANOVA analysis results showed that the collected throughflow differed with distance travelled along the trial trays, with significant differences shown in the post hoc tests between the 30cm samples and all the previous sample points for the non-bent species. However this did not necessarily mean there was a reduction in flow just that it pooled at the end of the tray. The Bents do not show significantly different throughflow between the sampled points suggesting that throughflow was similar along the length of the tray. The Bents also tended to have higher values of collected throughflow compared to the non-Bent species. This suggests that the Bents are promoting more of the simulated runoff to be infiltrated rather than pooling at the end of the tray like the non-bent species. This is beneficial as encouraging runoff to infiltrate will help deposit suspended solids. Sun and Davis (2007:1608) suggest that 88-97% of heavy metal input by runoff is captured in the soil medium. However, these heavy metals can only be captured if they are deposited. With the Bents encouraging more throughflow hence infiltration they seem a more logical choice for achieving this.

However, the fact that there was no significant difference in throughflow with both of the sowing densities suggests that infiltration characteristics were more important to the hydraulic performance of vegetated surfaces than the grass species that were used. Johnson et al. (2003:21) simulated both indoor and outdoor swales and concluded that the species of grass used made little difference as they showed similar hydraulic performance. Other factors such as soil saturation are just as influential on the performance of vegetative SUDS. Firstly it is critical to the infiltration of runoff and therefore the reduction of flows. Having a soil that is compacted or not capable of suitable infiltration would significantly reduce the performance of a vegetative surface like a swale regardless of the grass type (EPA, 1999:2-3). The deposition of total suspended solids (TSS) has also been shown to clog soil pores, decreasing infiltration capacity (Deletic and Fletcher, 2006). As well as soil conditions, runoff velocity is also an important factor in the retention of runoff with numerous sources stating that extreme velocities above 2m/s can have a severe impact on the efficiency of a vegetative surface (Woods-Ballard et al 2007:253; EPA, 1999:2). CIRIA recommend a maximum inflowing runoff velocity of $1ms^{-1}$ into vegetated surfaces with speed exceeding this reducing the overall performance (Wood-Ballard et al 2007:252). Deletic and Fletcher (2006:262) suggested that different grasses would influence the velocity, encouraging infiltration. Wilson et al. (2004) suggested that denser grasses may be more suitable for their ability to increase the resistance to runoff passing through, slowing velocity and encouraging infiltration. The Bents support these views that a dense grass would be more effective from a hydraulic point of view.

Overall design is also fundamental, with characteristics such as geometry of the SUDS device and hydraulic residence time (HRT) contributing to overall performance. Firstly the geometry (e.g. the length, slope etc) provides the overall basis for the performance of the grasses (Escarameia et al. 2006). The grass species and density have much more influence on facts such as HRT. Colwell et al. (2000) stated that a HRT of 9 minutes is necessary for effective performance and although this was not achieved in the trials, the Bents showed potential in reducing the velocity of the simulated runoff to a point where it could infiltrate. Of course this was only a small trial, and a larger study might show a greater distinction in the performance of species.

Deletic (2005) suggested that the grass type was an important factor with greater densities encouraging more sedimentation by slowing the flow of water. This trial has demonstrated that the Bents, sown at a higher density appear to encourage infiltration compared to the non-bent species. Overall the trial highlighted points made by Colwell et al. (2000) and Latin and Barrett (2005) that other factors such as soil conditions and overall design of SUDS are critical to performance of a swale or filter strip.

## 5.6 – Limitations

Laboratory studies present a number of limitations mainly due to their inability to recreate complex natural conditions. This study used strategies to create uniform test conditions though there will always be aspects that cannot be completely controlled and this must be recognised to make valid conclusions. One such limitation was the street dust used, which although homogenised to a degree, was still highly variable making it difficult to test whether it had a consistent effect on the grasses. Reasons for the use of this material have been explained in previous chapters. Another limitation was that grasses were grown in pots, which is unrealistic of how they might perform in a typical vegetated surface. The pots could have allowed material to move down the side and base of the pots, something that would not happen in the natural environment. The pots also confined the street dust, instead of in the natural environment, where a runoff event would re-suspend it on the surface and effectively remove it from the area. This study simulated an extreme event and how the grasses would respond to high levels of heavy metals attached to the street dust so that grasses that performed well in these conditions could be considered for their suitability in swales or filter strips.

The testing design would have benefitted from improvement, firstly with the collection of the root material which did not completely represent the roots in the pot. Approximately 4g of root was collected from each of the sampled pots; however there was no uniform sampling of pots. This meant there could be variations between the samples that would give different results. ANOVA analysis results showed no significant differences in metal root concentration with treatments even though a significant change was noted for shoot concentrations; two aspects of a grass that are closely linked in regard to metal up take. This was further complicated as it was not possible to determine whether all of the compost was cleaned off the root samples, though great care was taken to ensure this. The only way to make reliable conclusions about the roots would be to use all of the material from each pot which would be particularly difficult as some of the grasses had fine and fragile root structures. Another aspect of the sampling that could have affected results was that Layer B was extensively sampled to determine if the street dust treatments had an effect on the heavy metal concentrations. ANOVA analysis showed that metal concentrations in the compost showed no significant difference with street dust treatments with mineral magnetism results indicating that the street dust was captured in Layer A with only a small amount migrating down into Layer B. This indicates that a more extensive sampling of both Layers A and C may have been more revealing of the effects of the street dust treatments. Issues also arose with the sampling of biomass due to the two different sowing densities that were used. By trying to realistically represent how each species would be planted in the environment it became difficult to measure performance in biomass production against species sown at different sowing densities. Also it was difficult for the same reason to determine whether the street dust was having an affect on biomass production.

The hydraulic retention trials exhibited limitations as larger amounts of throughflow were collected at the end of the trays (30cm) rather than along the trays length. This indicated that the water just travelled across the surface and pooled at the end of the tray, before infiltrating and becoming throughflow measured beneath the tray. Possibly this was due to the angle of the tray being too steep to allow the simulated runoff to slow enough to infiltrate. Also the length of the tray may have been insufficient to allow the simulated runoff to drain properly along the length of the tray and resulted in largest measurements of throughflow being recorded at 30cm for all the grasses. However, Table 4.18 shows that the grass species all encourage more throughflow along the length of the tray compared to that recorded with a bare compost surface. This indicated that the grasses were slowing the velocity of simulated runoff, encouraging some infiltration. With no difference between the grasses at this scale, larger models would provide better discrimination between those grasses which encourage infiltration without interference from artificial boundaries such as the confines of the tray. Larger models would also provide a more realistic representation of hydraulic performance with swales recommended as having a longer length to be fully effective from a water quality perspective (Burkhard et al. 2000:201; Wood-Ballard et al 2007:258).

The last limitation which was problematic throughout this study was the variability in the results obtained. The first and most significant factor was the variability in chemistry of the street dust which contributed to the variability in the heavy metal concentrations found in the roots and shoots. Also as previously discussed possible weaknesses in the method (e.g. cleaning of the roots) could have further influenced the variability of the results. With such large variability it is difficult to draw clear and precise conclusions especially with statically analysis which can be easily influenced by more extreme results.

The final chapter summarises the findings of this study providing recommendations of suitable grass species and possibilities for further study.

# 6.0 Conclusions

This chapter summarises the key findings from both the pollutant retention and hydraulic trials and their practical application. Using the analysis of the results in the previous chapter recommendations of grasses that would be potentially suitable for vegetative SUDS such as swales and filter strips were made. This chapter also examines the aspects of the study which could be further developed.

## 6.1 Overview of the Study & Possible Practical Applications

The pollutant retention study showed that compost Layer B did not show signs of street dust causing significant difference to the heavy metal concentrations. Magnetic susceptibility analysis also showed, for all species, including the bare compost control, that Layer A exhibited the largest concentrations. Layer C had a slightly larger magnetic susceptibility than Layer B, being a possible indication of movement of street dust down the sides of the pots. This illustrated that the street dust was either too large to migrate freely through the compost profile or was perhaps having its movement impaired by the presence of the grass roots. Also according to the magnetic susceptibility analysis the Bents, which had more roots on the surface of the compost, had higher susceptibility, indicating larger amounts of street dust. From a practical perspective it shows that the majority of heavy metals (attached to the street dust would be kept in the upper sections of compost and therefore be prone to re-suspension. The issue with magnetic susceptibility is that it only highlights the materials with magnetic properties and not all of which would necessarily include heavy metal concentration. Particles from materials such as tyres would not be magnetic but still high on concentrations of metals such as Zn and Cd. Heavy metal analysis showed that species such as *F. rubra* and *F. arundinacea* had higher heavy metal concentrations in their compost cores even though they have lower susceptibility than the Bents. Although re-suspension of settled sediments in a swale can be reduced with design features such as check dams (Woods-Ballard et al. 2007: 254) it could be further reduced by using species that allow more sediment to migrate into the soil to limit the amount re-suspended by further runoff events. Grasses such as the Bents that displayed dense root systems on the surfaces may further limit this migration and possibly encourage re-suspension.

The concentration of heavy metals found in the grass shoots were largely within limits that were deemed healthy for the grasses (Kabata-Pendias, 2001; Hopkins and Hüner, 2009) although all the grasses did have Ni concentrations that would be toxic. *A. canina*, *A. capillaris syn.tenuis* and *P. pratensis* stood out in particular as having higher concentrations of heavy metal in their shoots and roots than the other species. *A. canina* had the highest concentrations by far in the shoots possibly due to physical accumulation through the shoots when the street dust was applied to the pots. This has interesting practical applications as particular species could be chosen to target particular heavy metal pollutants. This means that particular hot spots could be targeted by swales and filter strips more effectively. However, with there being large variations in the street dust it is difficult to give concrete evidence that particular grasses accumulate significant amounts of heavy metals compared to the other tested species. Also it might be considered ill advised to have large concentrations of heavy metals accumulating in shoots as it could firstly pose a hazard to animals and humans but would also add extra cost to maintenance as the material would need to be disposed of as hazardous waste (Wood-Ballard et al. 2007). If this was not an issue, then the Bents also have the added advantage of often having the highest concentrations in the roots, probably due to the stoloniferous root systems that they develop. If accumulation was an issue in the shoots then perhaps species could be chosen based upon their root accumulations with minimal transfer to the shoots. The lack of mobility of the street dust associated heavy metals illustrates that in real world situations grass phytoremediation might have a limited affect with only a small proportion of the heavy metals being transported to the shoots. However, this study had a short timescale whereas in the real world, swale grasses would be growing for longer and therefore have potential for greater street dust accumulation. A larger proportion of heavy metals were found in the compost as corroborated by Sun and Davis (1998:258) who found that up to 97% of heavy metals were captured and retained in the soil.

The hydraulic trials were inconclusive in providing a recommendation of a grass species based on its hydraulic performance. Analysis of the Bents revealed that there was no significant difference with throughflow between the species and along the distance of the tray. However, the non-bent species showed significant increases in throughflow, although mainly at the end of the tray. This indicated that the simulated runoff just ran to the end of the tray and pooled, illustrating poorer performance compared to the Bents. The Bents, in particular *A. canina*, showed increased throughflow (hence infiltration) along the length of the tray compared to the non-bent species. It is likely that this can be attributed to their denser sowing. However, all grasses did record more throughflow along the length of the tray than the control, showing that the presence of vegetation did have a beneficial effect. In hindsight the trays were too small to give accurate information on the individual species performance. Further trials are needed to determine the trapping efficiency of the grasses along the length of a vegetated surface as well as their ability to slow runoff and encourage infiltration. It also provides a starting point to explore the targeting of specific grass sowing densities to improve the hydraulic performance of swales or filter strips. Increasing the hydraulic performance would also be likely to have a positive knock on effect to encourage deposition of suspended solids (Wilson et al. 2004:206). Grass species accounts for one factor affecting hydraulic retention with surface characteristics such as soil saturation affecting overall performance of a swale or filter strip. Other studies by Colwell et al (2000), Latin and Barrett (2003) and Wood-Ballard et al (2007) all indicate that the overall design of the vegetative surface (e.g. the slope it is built on, its length or the presence of check dams) is more important for maximising their performance than grass species.

## 6.2 Recommendations of Species for Vegetated SUDS

The recommendation of suitable grasses for vegetated surfaces is based on the information gained through both the pollutant and hydraulic retention trials along with information from the Highways Agency, (2006) regarding individual characteristics of grasses. The hydraulic retention trials alone did not provide sufficient information for recommendations as results showed no significant difference between the grasses sown at different densities, indicating that grass species is only one minor factor in hydraulic performance rather than other factors such as compost conditions and design characteristics (e.g. length of device and slope) as highlighted by Deletic and Fletcher (2006). The Bents were superior in slowing the simulated runoff and encouraging infiltration rather than just allowing the runoff to settle at the end of the tray. This was probably related to the different densities at which the grasses were sown. However, the grasses all show an increase in collected throughflow compared to the control. Prolonging the presence of runoff in the tray allowed more infiltration, reflecting results found in similar studies by Han et al (2005). As HRT is suggested to be a minimum of 9 minutes, the length and design of the vegetative surface seemed to be more important that the actual species of grass.

The pollutant retention trial highlighted that *A. canina* and *P. pratensis* accumulated more heavy metals than the other grasses during the trial. Compost heavy metal concentrations showed biggest decreases with these two species which reflected increases in the shoots and the roots (especially for *A. canina*). With more heavy metals being accumulated from the compost and translocated to the shoots, mowing which is part of routine maintenance would allow these metals to be removed (Wilson et al, 2004). Other species such as *A. capillaris syn.tenuis* and to some extend *A. stolonifera* also showed promise with both species showing large concentrations in the roots and shoots. However, both species do not show a significant increase from the control, perhaps due to lack of availability of heavy metals in the street dust meaning that when ranked they were lower than their capabilities suggested. This makes them an interesting species to consider for further study. All the species except *P. pratensis* and *A. capillaris syn.tenuis* showed significant differences with street dust treatment in Cu, Pb and Zn indicating that they reacted to the increased bio-availability of heavy metals available from the street dust. Another interesting characteristic further encouraging the use of both these species was that *P. pratensis* showed accumulation of soluble heavy metals from Layers A and B. Although *A. canina* did not show the same pattern this may have been masked by the application of street dust to the surface layer (A). A combination of these of stoloniferous roots and deeper penetrating roots would allow for maximum heavy metal removal from all parts of the compost. The increased concentration of heavy metal in the roots of *A. capillaris syn.tenuis* and *A. stolonifera* also suggest that their stoloniferous root systems could be highly beneficial in removing soluble heavy metals from settled sediments in a SUDS device.

Growth characteristics are also vital in recommending grasses. Traits such as rapid establishment, capability of developing in saturated soils, being drought resistant and capable of recovering from large amounts of wear, give grasses a better chance of surviving longer and having a greater effect on heavy metal removal. Table 2.2 showed that while *A. canina* and *P. pratensis* are slow to establish and grow, other species such as *L. perenne* and *F. rubra* grow rapidly with *L. perenne* being especially good at recovery from wear (Highways Agency, 2006). This combination of characteristics would enable a mixed swale not only to survive and thrive but also to increase heavy metal uptake. This is important when the concentrations of heavy metals being taken up are only small. A study by Sun and Davis (2007:1608) found that a maximum of just 3% of heavy metals were transported to the shoots of grass. The majority of the contaminants are caught and retained in the soil and unlikely to be up taken into the plant material due to the immobile nature of the heavy metals, particularly when attached to particulates (Pitt et al. 1999:227). This is typical of the street dust used in this trial, which showed a lack of heavy metals being leached except for Ni.

Current grass mixtures such as 25% *L. perenne*, 25% *P. pratensis*, 30% *F. rubra*, 10% Chewing Fescue (*Festuca rubra var. commutate*) and 10% *A. capillaris syn.tenuis* or *A. stolonifera* are recommended by CIRIA (Wood-Ballard et al, 2007), whereas the Highway Agency suggest a mixture of 20% *L. perenne*, 10% Highland Bent (*Agrostis castellana)* , 20% *F. rubra var. commutate*, 40% Slender Creeping Fescue (*Festuca rubra litoralis*) and 10% *P. pratensis* (Highways Agency – 2006:21). The different mixtures reflect differences in location as both the Highway Agency (2006) and Balmforth et al. (2006) state that indigenous grasses should be used where possible. From this study *A. canina* and *P. pratensis*, which only appear in small percentages in the above recommended mixtures, seem to be the best grasses to be recommended due to their increased accumulation of heavy metals compared to other species trialled. The other bents, *A. capillaris syn.tenuis* and to some extent *A. stolonifera* are also highly recommended, with stoloniferous roots allowing available metals to be taken up from the surface although *A. stolonifera* did not perform as well compared to other species. The Bents in general also had better hydraulic performance making them suitable for use in SUDS devices such as swales.  Species such as *L. perenne* or *F. rubra* do warrant use for their physical attributes as well as their ability to accumulate heavy metals from street dust, although the focus of further studies should be on the Bents and *P. pratensis*. Further studies on larger scale swales and filter strips would allow the recommended grass mixture to be refined, with suitable percentages of each grass species chosen to maximise both the up take of heavy metals from the soil but also retention of runoff.

## 6.3- Further Development of Study

A further development of this study would be to upscale it to make use of a more realistically sized vegetated surface such as those used in studies by Deletic and Fletcher (2006) and Johnson et al (2006). These would be constructed to the recommended specification for vegetated surfaces (either filter strips or swales) using the selection of grasses recommended in Section 6.2. They would provide a more realistic example of a swale or filter strip as one grass would not be used alone in a vegetated surface. This would also mean that comparisons could be tested between recommended mixtures sourced from current examples of vegetated surfaces or from consultation with practitioners. Once the test beds had matured, tests could be performed in three main areas.

1. Hydraulic flow: on a previously saturated test surface, a known volume of simulated rainfall would be applied at a variety of intensities (10, 15, 20 & 25 mm $h^{-1}$) and the volume of runoff measured using a Gerlach Trough located at the end of the slope (Deletic and Fletcher, 206:263; Rüttimann et al, 1995:128). These surfaces would be much larger than the current hydraulic trial thus similar to that found in a real world environment. Background experiments would be conducted using bare compost, artificial turf and an impermeable surface, such as concrete.
2. Sediment trapping: similar experiments to those carried out above, but would be undertaken with street dust applied to the upper slope of the model using a Gerlach Trough to collect the runoff plus sediment. Background experiments will be run similar to those given above.
3. Mixtures: a variety of mixtures that use different percentages of Bents (predominately *A. canina*) and *P. pratensis* would be compared to determine the most suitable and effective mixture for a vegetated surface.

Issues were also raised from the trials that could be further explored. Firstly there could be an improvement on the use of street dust. As previously mentioned the street dust was highly variable and therefore made conclusions difficult. If street dust was used for further testing a more robust method could be used that would attempt to further limit the variation such as collecting the material by hand from a smaller number of sites. Synthetic material could also be developed in an attempt to better measure the grasses accumulation of heavy metals. Secondly there was an issue regarding whether the accumulation of the heavy metals was a biological process through the roots or a physical process from applying street dust from above with accumulation directly through the shoots. A possible solution would be for a trial where street dust was applied before the grasses had grown so that street dust was not applied to their shoots directly. If heavy metals were analysed in the same way as this trial, comparisons could be made as to whether particular species such as *A. canina* really did accumulate more heavy metals from the compost as a result of a biological process. Lastly the effect of street dust on biomass could be further explored with small suggestions that the non-bent species may have increased yield with the 20g and 40g street dust treatments. One of the difficulties with this trial was that there were two seeding densities ($20g/m^2$ & $35g/m^2$) so future trials could be conducted with one sowing density for all species. This would provide comparable data of whether the grasses had additional biomass production with the application of pollutants.

Another aspect would be to analyse the effect of natural vegetation migrating into the vegetated surfaces and how that would affect the performance both hydraulically and with pollutant retention over an extended period of time. Native vegetation could affect the vegetation in different ways and therefore must be a consideration in the long term performance. Longer term performance issues could also be monitored to note the affects of deposited material which could reduce efficiency by filling in the pores of the compost, reducing infiltration and therefore the hydraulic and sediment removal performance.

Undertaking these experiments would provide further information on the hydraulic performance of the grass species which was not fully explored by this study. This research simply acted as a preliminary study to determine if any of the grasses showed particular promise. Mixtures of the recommended species should be further investigated to provide the best performing mixture for use in vegetated SUDS.

# References


Alloway B.J. (1995) Soil Plant relationship of heavy metals: Foliar Absorption. (eds) by Alloway B.J. (2nd Edition) Heavy Metal in Soils. London: Blackie Academic and Professional [online] Available from: <http://books.google.co.uk/books?hl=en&lr=&id=CX1GwLBhkC4C&oi=fnd&pg=PA3&dq=atmospheric+deposition+heavy+metals+on+grass+shoots&ots=WaWbfegz31&sig=KPNCiCAx0cKTIarKm_zs70fx8N0#v=onepage&q=&f=false> [03/04/10]

Antoniadis V., Robinson J.S., Alloway B.J. (2008) 'Effects of short-term pH fluctuations on cadmium, nickel, lead, and zinc availability to ryegrass in a sewage sludge-amended field.' *Chemosphere* 71, (4) 759-764

Apostolaki S., Jefferies C., Wild T. (2006) 'The social impacts of stormwater management techniques.' *Water Practice & Technology* **1**(1), 1-8

Araújo G.C.L., Gonzalez M.H., Ferreira A.G., Nogueira A.R.A., Nóbrega J.A. (2002) 'Effects of acid concentration on closed –vessel microwave-assisted digestion of plant material.' *Spectrochimica Acta Part B* **57**, 2121-2132

Bablake Weather Station (Coventry) (n.d) – Available from: <bws.users.netlink.co.uk> [12/12/08]

Balmforth D., Digman C., Kellagher R., Bulter C. (2006) Design for Exceedance in Urban Drainage: Good Practice (C635) London: CIRIA

Barrett M.E., Irish L.B., Malina Jr J.F., Charbeneau R.J. (1998) 'Characterization of highway runoff in Austin, Texas area.' *Journal of Environmental Engineering* Feb, 131-137

Barrett R. (2000) 'Dust, Measurements of Trace Elements in.' eds. By Meyers R.A. *Encyclopaedia of Analytical Chemistry*. Oxford: John Wiley & Sons Ltd

Begonia M.T., Begonia G.B., Ighoavodha M., Gilliard D. (2005) 'Lead accumulation by Tall fescue (festuca arundinacea Schreb.) grown on a lead-contaminated soil.' *International Journal of Environmental Research and Public Health* **2**, (2) 228-233

Bidar G., Garcon G., Pruvot C., Dewaele D., Cazier F., Douay F., Shirali P. (2007) 'Behaviour of trifolium repens and Lolium perenne growing in a heavy metal contaminated field: Plant metal concentrations and phytotoxicity.' *Environmental Pollution* **147**, 546-553

Blanco-Canqui H., Gantzer C.J., Anderson S.H., Alberts E.E., Thompson A.L. (2004) 'Grass barrier and vegetation filter strip effectiveness in reducing runoff, sediment, nitrogen and phosphorus loss.' *Soil Science Society of America Journal* **68**, 1670-1678

Bond W., Davies G., Turner R. (2007) 'The biology and non-chemical control of Creeping Bent (*Agrostis stolonifera* L.)' [online]
Available from < http://www.gardenorganic.org.uk/organicweeds/downloads/agrostis%20stolonifera.pdf> [01/09/09]

Bonnet M. Camares O., Veisseire P. (2000) 'Effects of zinc and influence of *Acremonium lolii* on growth parameters, chlorophyll *a* fluorescence and antioxidant enzyme activities of ryegrass (*Lolium perenne* L. cv Apollo).' *Journal of Experimental Botany* **51**(346), 945-953

Brown J.N., Peake B.M. (2006) 'Sources of heavy metals and polycyclic aromatic hydrocarbons in urban storm water runoff.' *Science of the Total Environment* **359**, 145-155

BSM Catalogue, Available from:
<http://www.bshamenity.com/bshamenity/UserFiles/File/Brochures%20and%20Publications%202009/Shortform%20%202009.pdf > [12/12/08]

Burkhard R., Deletic A., Craig A. (2000) 'Techniques for water and wastewater management: a review of techniques and their integration in planning.' *Urban Water* **2,** 197-221

Burrell B.C., Arisz H., (2006) 'Urban drainage infrastructure planning and design considering climate change.' *IEEE EIC Climate Change Technology Conference.* Ottawa, ON

Chatfield P. (2007) SUDS progress: An environment agency perspective [online] Available from: http://sudsnet.abertay.ac.uk/documents/PRChatfield_EA-Sudsnet260307.pdf [01/04/10]

Charlesworth S., Everett M., McCarthy R., Ordonez A., Miguel E. (2003) 'A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West Midlands, UK.' *Environmental International* **29**, 563-573

Charlesworth S.M., Lees J.A. (1997) 'The use of mineral magnetic measurements in polluted urban lakes and deposited dusts, Coventry, UK.' *Physics and Chemistry of the Earth* **22,** (1-2) 203-206

Charlesworth S.M., Lees J.A. (2001) 'The application of some mineral magnetic measurements and heavy metal analysis for characterising fine sediments in an urban catchment, Coventry, UK.' *Journal of Applied Geophysics* **48**, 113-125

Chocat B., Ashley R., Marsalek J., Matos M.R., Rauch W., Schilling W., Urbonas B. (2007) 'Toward the sustainable management of urban stormwater.' *Indoor and Built Environment* **16**, 273-285

Christian G.D. (2003) *Analytical Chemistry*. Hoboken, NJ: John Wiley & Sons

CIRIA (2000) *Sustainable Urban Drainage Systems: Design manual for England and Wales* (C522), London: CIRIA

CIRIA (2001) *Sustainable urban drainage systems: best practice manual for England, Scotland, Wales and Northern Ireland.* London: CIRIA

CIRIA (2005) 'Sustainable Drainage News.' London: CIRIA

CIRIA (2007) 'Sustainable Drainage News.' London: CIRIA

Civeira G., Lavado R.S. (2008) 'Nitrate losses, nutrients and heavy metals accumulation from substrate assembled for urban soil reconstruction.' *Journal of Environmental Management* **88**, 1619-1623

Clayton W.D., Harman K.T., Williamson H. (2008) GrassBase - The Online World Grass Flora. [online] Available from: http://www.kew.org/data/grasses-db.html. [02/04/10]

Clesceri L.S., Greenberg A.E., Eaton A.D. (1998) *Standard Methods for the Examination of Water and Wastewater* (20th Edition).Maryland, US: United Book Press, 1-13

Colwell S.R., Horner R.R., Booth D.B. (2000) Characterization of performance predictors and evaluation of mowing practices in bio-filtration swales [online] Available from
<http://water.washington.edu/Research/Reports/swale%20mowing.pdf> [11/02/09]

Curtis M. C. (2002) Street Sweeping for Pollutant Removal [online] Available from: <http://www.montgomerycountymd.gov/content/dep/publications/pdf/streetsweeping.pdf> [01/11/08]

Davies D.E. Section 2: Individual Elements: Copper. (1989) Eds. by Alloway B.J. *Heavy Metals in Soil*. Glasgow: Blackie

Dearing J.A. (1999) Environmental Magnetic Susceptibility: Using the Bartington MS2 System (OM0409). Oxford: Bartington Instruments

Deletic A.(2001) 'Modelling of water and sediment transport over grassed areas.' *Journal of Hydrology* **248**, 168-182

Deletic A. (2005) 'Sediment transport in urban runoff over grassed areas.' *Journal of Hydrology* **301**, 108-122

Deletic A., Fletcher T.D. (2006) 'Performance of grass filters used for storm water treatment – a field and modeling study.' *Journal of Hydrology* **317**, 261-275

De Miguel E., Iribarren I., Chacon E., Ordonez A., Charlesworth S. (2007) 'Risk based evaluation of the exposure of children to trace elements in playgrounds in Madrid (Spain).' *Chemosphere* **66**, 505-513

DLF Trifolium (n.d.) Available from: <http://www.iog.org/documents/09.50IOGRIGHTGRASSRIGHTPLACE.pdf> [08/08/09]

Elias C.O. (1982) 'The effect of low phosphorus on nine grass cultivars for derelict land reclamation.' *Journal of Applied Ecology* **19**, 239-248

Elik A. (2003) 'Heavy metal accumulation in street dust samples in Sivas.' *Communications in Soil Science and Plant Analysis* **34**, (1&2) 145-156

Ellis J.B., Scholes L., Revitt D.M., Oldham J. (2004a) 'Sustainable urban development and drainage.' *Municipal Engineer* **157**, 245-250

Ellis J.B., Deutsch J.C., Mouchel J.M., Scholes L., Revitt M.D. (2004b) 'Multicriteria decision approaches to support sustainable drainage options for treatment of highway and urban runoff.' *Science of the Total Environment* **334-335**, 251-260

Ellis J.B., Mitchell G. (2006) 'Urban diffuse pollution: Key data information approaches for the Water Framework Directive.' *Water and Environment Journal* **20**, 19-26

Environmental Agency (n.d.) [online] Available from: <http://www.environment-agency.gov.uk/research/planning/33714.aspx> [08/08/09]

Environmental Service Association (n.d.) PAS 100: Specification for composted materials. [online] Available from: <http://www.esauk.org/work/briefings/pas100.asp> [19/07/09]

EPA (1999) Stormwater Technology Fact Sheet: Vegetated Surfaces. [online] Available from: <http://www.epa.gov/owm/mtb/vegswale.pdf-Accessed 30/07/09> [21/07/09]

Eriksson E., Baun A., Scholes L., Ledin A., Ahlman S., Revitt M., Noutsopoulos C., Mikkelsen P.S. (2007) 'Selected stormwater priority pollutants – a European perspective.' *Science of the Total Environment* **383**, 41-51

Escarameia M., Todd A.J., Watts G.R.A. (2006) 'Pollutant removal ability of grassed surface water channels and swales: Literature review and identification of potential monitoring sites.' Published Project Report PPR169. TRL Limited [online] Available from: <http://www.ha-research.gov.uk/projects/projectdocuments.php?method=download&ID=272> [08/10/08]

Evanylo G.K., Abaye A.O., Dundas C., Zipper C.E., Lemus R., Sukkariyah B., Rockett J. (2005) 'Herbaceous vegetation productivity, persistence and metal uptake on a biosolids-amended mine soil.' *Journal of Environmental Quality* **34**, 1811-1819

European Union (2000) Water Framework Directive (2000/60/EC). [online] Available from: <http://www.ha-research.gov.uk/projects/projectdocuments.php?method=download&ID=272> [24/11/08]

Ferreira-Baptista L., Miguel D.E. (2005) 'Geochemistry and risk assessment of street dust in Luanda Angola: A tropical urban environment.' *Atmospheric Environment* **39**, 4501-4512

Garcia R., Millian E. (1998) 'Assessment of Cd, Pb and Zn contamination in roadside soils and grasses from Gipuzkoa (Spain).' *Chemosphere* **37,** (8) 1615-1625

Grasscete (n.d.) Grassblock Brochure [online] Available from: <http://www.grasscrete.com/pdfs/GrassblockBrochure.pdf > [11/08/08]

Han J., Wu J.S., Allan C. (2005) 'Suspended sediment removal by vegetative filter strip treating highway runoff.' *Journal of Environment Science and Health* **40**, 1637-1649

Harris D.C., (1999) *Quantitative Chemical Analysis* (5th Edition), US: W.H Freeman and Company, 825-827

Highways Agency (2006) Design Manual for Roads and Bridges -Volume 4 Geotechnics and drainage, Section 2 (HA103/06) [online] Available from: <http://www.standardsforhighways.co.uk/dmrb/vol4/section2/ha10306.pdf> [20/02/09]

Hopkins W.G., Hüner N.P.A. (2008) *Introduction to Plant Physiology* (4th Edition). Hoboken, New Jersey: John Wiley & Sons

Jackson, J. I., Holt, C. P., Newman, D. R. & Clarke, D. J. (2006) Planning for environmental and ecological gain with Sustainable Urban Drainage Systems (SUDS): monitoring and evaluation of a storm water drainage system within a new housing development at Upton, Northampton, UK. In: *Proceedings of the 14 th Annual IALE( UK ) conference at Oxford Brookes University : Water and the landscape: The landscape ecology of freshwater ecosystems*. Eds: Davies, B. & Thompson, S., p47-53.

John Innes (n.d.) <http://www.johninnes.info/technical.htm> [14/12/08]

Johnson P.D., Clark S., Pitt R., Durrans S.R., Urrutia M., Gill S., Kirby J. (2003) 'Metal removal technologies for stormwater.' Industrial Water Conference (WEF): San Antonio, 1-26

Kabata-Pendias A. (2001) *Trace elements in soils and plants* (3rd Edition). London: CRC Press

Kalis E.J.J., Temminghoff E.J.M., Visser A., Van Riemsduk W.H. (2007) 'Metal Uptake by Lolium Perenne in contaminated soils using a four-step approach.' *Environmental Toxicology and Chemistry* **26**, (2) 335-345

Kechavarzi C., Pettersson K., Leeds-Harrison P., Ritchie L., Ledin S. (2007) 'Root establishment of perennial ryegrass (L. Perenne) in diesel contaminated subsurface soil layers.' *Environmental Pollution* **145**, 68-74

Killham K.(1994) Soil Ecology. Cambridge University Press. Cambridge [online] Available from: <http://books.google.co.uk/books?id=zDIaumF3MCYC&pg=PA24&lpg=PA24&dq=anaerobic+conditions+effects+on+pH+in+soil&source=bl&ots=7ErS0w_H-r&sig=EX8Yru8VnBf_Jw-OdgDgkfUosqo&hl=en&ei=Y7WTS8ucJ8uNjAfAp-iACw&sa=X&oi=book_result&ct=result&resnum=9&ved=0CCwQ6AEwCDgK#v=onepage&q=anaerobic%20conditions%20effects%20on%20pH%20in%20soil&f=false> [07/03/10]

Kinnear P.R., Gray C.D. (2009) *SPSS 16: Made Simple*. East Sussex: Psychology Press

Kirby J.T. (2005) 'SuDS – Innovation or tried and tested practice?' *Municipal Engineer* **158**, 115-122

Kurdziel M., Prasad M.N.V., Strzalka K. (2004) 'Photosynthesis in Heavy Metal Stressed Plants.' Prasad M.N.V. (eds) Heavy Metal Stress in Plants: From biomolecules to ecosystems (2nd Edition) [online] Available from: <http://books.google.co.uk/books?id=LmjqrKXXP1cC&pg=RA2-PA1915&lpg=RA2-PA1915&dq=foliar+absorption+of+heavy+metals&source=bl&ots=vGMW8b7bCQ&sig=8qCjM6xCwWDI7adUp8z_GBbyc2M&hl=en&ei=apezS8aKG8r44gbyz5jQAg&sa=X&oi=book_result&ct=result&resnum=10&ved=0CDAQ6AEwCQ#v=onepage&q=foliar%20absorption%20of%20heavy%20metals&f=false> [03/04/10]

Latin A.P., Barrett M.P. (2005) Design and Pollutant Reduction of Vegetated Strips and Swales Proceedings of the 2005 World Water and Environmental Resources Congress. EWRI 2005: Impacts of Global Climate Change; Anchorage, Alaska; USA; 15-19 May 2005.

Low Impact Development Centre (n.d.) Trapezoidal Grassed Swale: [online] Available from: <http://www.lowimpactdevelopment.org/epa03/LIDtrans/Ex_Swale.pdf> [08/02/09]

Martin P., Turner B., Waddington K., Dell J., Pratt C., Campbell N., Payne J., Reed B. (2000) 'Sustainable Urban Drainage Systems: Design Manual for England and Wales.' CIRIA: London

Martin P., Turner B., Payne J., Elliot C., Reed B. (2001) 'Sustainable Urban Drainage Systems: Best practice manual (C523).' London: CIRIA

Maynard R.L. (2001) eds. by Brimblecombe P. Maynard R.L. *The Urban Atmosphere and Its Effects*. London: Imperial College Press

Ministry of Agriculture, Fisheries and Food (1986) The Analysis of Agricultural Material (RB 427, 3rd Edition). London: HMSO

Monsanto Company and Scotts Company. (2003) APHIS Preliminary Risk Assessment on the Petition for a Determination of Nonregulated Status for Creeping Bentgrass (*Agrostis stolonifera*) Genetically Engineered (Event ASR368) for Tolerance to the Herbicide Glyphosate [online] <http://www.aphis.usda.gov/brs/aphisdocs/03_10401p_ra.pdf> [01/09/09]

Murray Y.G.P., Hendershot W.H. (2000) 'Trace metal speciation and bioavailability in urban soils'. *Environmental Pollution* **107**, 137-144

Patel J.A (2005) 'Briefing: A Review of CIRIA Report 142 on highway pollutants'. *Transport* **158**, 137-138

Pérez-de-Mora A., Madejón E., Burgos P., Cabrera F. (2006) 'Trace element availability and plant growth in a mine-spill contaminated soil under assisted natural remediation I. Soils.' *Science of the Total Environment* **363** (1-3), 28-37

Pierzynski G.M., Sims J.T., Vane G.F. (2000) 'Soils and Environmental Quality (2nd Edition)'. London: CRC Press

Pitt R., Clark S., Field R. (1999) 'Groundwater contamination potential for stormwater inflitration practices.' *Urban Water* **1**, 217-236

Pitt R., Williamson D., Voorhees J., Clark S. (2004) 'Review of historical street dust and dirt accumulation and washoff data.' [online] Available from: <http://rpitt.eng.ua.edu/Publications/Pollutant%20Sources/street%20dirt%20accum%20and%20washoff%20Pitt%20et%20al%20James%202004.pdf> [29/10/08]

Royal Horticultural Society (2006) 'Gardening Matters: Front Gardens.' [online] Available from: <http://www.rhs.org.uk/learning/research/gardeningmatters/documents/FrontGardens.pdf> [09/08/07]

Rüttimann M., Schaub D., Prasuhn V., Rüegg W. (1995) 'Measurement of runoff and soil erosion on regularly cultivated fields in Switzerland – some critical considerations.' *Catena* **25**, 127-139

Sansalone J.J., Cristina C.M. (2004) 'First flush concepts for suspended and dissolved solids in small impervious watersheds.' *Journal of Environmental Engineering* Nov, 1301-1313

Santibáńez C., Verdugo C., Ginocchio R. (2008) 'Phytostabilization of copper mine tailings with biosolids: Implications for metal uptake and productivity of Lolium perenne.' *Science of the Total Environment* **395**, 1-10

Shaw J.A. (1989) '*Heavy metal tolerance in plants.*' Boca Raton, Florida: CRC Press [online] Available from: <http://books.google.co.uk/books?hl=en&lr=&id=kvsPo4Et5scC&oi=fnd&pg=PA21&dq=Agrostis+canina+canina++heavy+metal+uptake&ots=wC462FAUTZ&sig=fTFZqTFiOhakCSCE47J7xNtauBo#v=onepage&q=&f=false> [02/09/09]

Shu W.S.,Ye Z.H., Lan C.Y., Zhang Z.Q., Wong M.H. (2002) 'Lead, zinc and copper accumulation and tolerance in populations of Paspalum distichum and Cynodon dactylon.' *Environmental Pollution* **120**, 445-453

Shilton V.F., Booth C.A., Smith J.P., Giess P., Mitchell D.J., Williams C.D. (2005) 'Magnetic properties of urban street dust and their relationship with organic matter content in the West Midlands, UK.' *Atmospheric Environment* **39**, 3651-3659

Stovin V.R., Swan A.D (2007) 'Retrofit SuDS – cost estimates and decision-support tools.' *Water Management* **160,** (WM4) 207-214

Sun X., Davis A.P. (2007) 'Heavy metal fates in laboratory bioretention systems.' *Chemosphere* **66**, 1601-1609

Taiz L., Zeiger E. (2006) *Plant Physiology* (4th Edition). Sunderland, Massachusetts: Sinauer Associates Publishers

Thomas R.A.P. (2005) *Bioremediation of former gasworks sites in the UK.* Eds. by Lens P., Grotenhuis T., Malina G., Tabak H. Soil and Sediment Remediation: Mechanisms, technologies and application. London: IWA Publishing [online]

<http://books.google.co.uk/books?id=T2e09Dn45U8C&printsec=frontcover#v=onepage&q=&f=false> [10/06/09]

Toronto and Region Conservation Authority (2006) Performance Evaluation of Permeable Pavement and a Bioretention Swale. [online] Available from: <http://www.icpi.org/myproject/Seneca%20College%20TRCA%202006%20report.pdf *pp 35-40*> [22/07/09]

Turfgrass Growers Association (n.d.) Available from: < http://www.turfgrass.co.uk/fact-sheets/grasses/> [12/12/08]

Van Huylenbroeck J.M., Lootens P., Van Bockstaele E., (1999) 'Photosynthetic characteristics of perennial ryegrass and red fescue turf-grass cultivars.' *Grass and Forage Science* **54**,267-274

White T.C., Howe J. (2002) 'Flooding and the Role of Planning in England and Wales: A Critical Review.' *Journal of Environmental Planning and Management* **45** (5), 735-754

Wild A. (1993) *Soils and the Environment*. Cambridge: Cambridge University Press

Wilson S., Newman A.P., Puehmeier T., Shuttleworth A. (2003) 'Performance of an oil interceptor incorporated into a pervious pavement.' *Engineering Sustainability* **156,** 51-58

Wilson S., Bray R., Copper P. (2004) *Sustainable drainage systems: Hydraulic, structural and water quality advice*. London: CIRIA

Woods-Ballard B., Kellagher R., Martin P., Jefferies C., Bray R., Shaffer P. (2007) *The SUDS Manual* (C697). London: CIRIA

Wong T.H.F., Fletcher T.D., Duncan H.P., Jenkins G.A. (2006) 'Modelling urban stormwater treatment – a unified approach.' *Ecological Engineering* **27**, 58-70

University of New Hampshire (n.d.) About Vegetated Swales [online] Available from: <http://www.unh.edu/erg/cstev/fact_sheets/veg_swale_fact_sheet_08.pdf> [08/02/09]

Xie S., Dearing J.A., Boyle J.F., Bloemendal J., Morse A.P. (2001) 'Association between magnetic properties and element concentrations in Liverpool street dust and its implications.' *Journal of Applied Geophysics* **48**, 83-92

Yu S.L., Kuo J., Fassman E.A., Pan H. (2001) 'Field test of grassed-swale performance in removing runoff pollution.' *Journal of Water Resources Planning and Management,* May/June, 168-171

Zander J.M. (2005) 'Road Sediment: Characterization and implications for the performance of vegetated strips for treating road runoff.' *Science of the Total Environment* **339**, 41-47

Zaurov D.E., Bonos S., Murphy J.A., Richardson M., Belanger F.C. (2001) 'Endophyte infection can contribute to aluminium tolerance in fine fescues.' *Crop Science* **41**, 1981-1984

# Appendix

## Appendix I: Ethics Consent Form

Ethical approval via either the University Ethics Committee (UEC) or School of Health and Social Sciences Ethics Committee (HSS EC) must be obtained by all staff/students prior to starting research and/or work with human subjects, animals, human tissue and controversial literary or artistic works with human or animal subjects.

| |
|---|
| **Which Committee will consider my project?** The HSS EC deals with all queries related to human subject issues and data related to/stored about humans. The UEC deals with all other ethical queries. |

The following checklist is intended to help you in your decision-making and should be completed prior to commencing work on <u>all</u> University projects (undergraduate, taught postgraduate and research). Work must not begin until approval has been given by the UEC or HSS EC, if required.

| | YES | NO |
|---|---|---|
| 1. Does the study involve human participants/animals? ** <br> ** - It is a legal requirement (Human Tissues Act 1961) that participants or patients give/gave written consent for the material (either directly or indirectly (e.g. using codes for which there exists an identification list)) to be used in research. If subsequent data obtained from these tissues is anonymised in such a way that it is impossible to identify the person from the material then it may be used without going back to them for further consent. | | X |
| 2. Will the study involve NHS patients, staff or premises? | | X |
| 3. Does the study involve participants who maybe or are unable to give informed consent? (e.g. children, people with learning disabilities, unconscious patients, animals) | | X |
| 4. Are drugs, placebos or other substances (e.g. food substances, vitamins) to be administered to the study participants? | | X |
| 5. Will the procedures use human tissue, blood or other body fluids, or include the penetration of a participant's skin or body orifices by any substance or device? | | X |
| 6. Will participants be presented with painful stimuli or high intensities of auditory, visual, electrical or other stimuli? | | X |
| 7. Could participants be required to undergo long periods of sleeplessness, confinement, sensory deprivation or any other form of stress? | | X |
| 8. Is there any foreseeable risk of physical, social or psychological harm to a participant arising from the procedure? | | X |
| 9. Will deception of participants be necessary during the study? | | X |
| 10. Will the study involve any invasion of privacy, or the accessing of confidential information about people without their permission? | | X |

| | | |
|---|---|---|
| 11. Does the project involve the collection of material that could be considered of a sensitive, personal, biographical, medical or psychological nature? | | **X** |

ڤ I have answered ‘Yes’ to at least one of questions 1-11.

**Does the project involve human subjects or records pertaining to them?** NO

ڤ **Yes** - application/project details must be submitted (together with this form) to the School of Health and Social Sciences’ Ethics Committee Chair (Dr R Jayram, room 315, Richard Crossman Building).

ڤ **No** - application/project details must be submitted (together with this form) to the University Ethics Committee Secretary (Mr M Ham, Research Section, room 114 Alan Berry Building).

**All materials submitted to the UEC and HSS EC will be treated confidentially. If you are unsure as to which Committee your paperwork should be forwarded to, please contact Dr Jayram (HSS EC Chair).**

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ڤ I have answered ‘Yes’ to at least one of questions 1-11 and **‘Yes’ to question 2**. The application/project details must be submitted to an appropriate external health authority ethics committee. Please contact the Chair of the HSS EC for further details.

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ڤ I have answered **NO** to all the above categories and do not consider that this application/project needs to be submitted to either the University Ethics Committee or School of Health and Social Sciences’ Ethics Committee. I accept that I am responsible for that decision and its consequences.

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**Where do I send the form?**

Student Projects
Form to be retained by Director of Studies or Supervisor and copied to the following:

1) For Research Students – School Research Degrees Sub-Committee Secretary
2) All other student projects - School Office

Staff Projects
Form to be copied to the School Director of Research.

Student Signature ………………………………………..**PRINT NAME**…*Andrew Waite* . School – *BES* Date…………

Signature 2 ……………………………………………….. **PRINT NAME** *Sue Charlesworth* School – *BES* Date…………

(*Director of Studies)*

## Appendix II: Significant Post Hoc Results from One-Way ANOVA on Different Street Dust Treatments for Shoots

### A: Significant Post Hoc Results for the Control

| Species (I) | Species (J) | Heavy Metal | Mean Difference (I-J) | Sig. |
|---|---|---|---|---|
| A. capillaris syn.tenuis | *A. stolonifera* | Cd | 0.636* | 0.030 |
| | *P. pratensis* | | 0.688* | 0.020 |
| | *F. rubra* | | 0.690* | 0.020 |
| | *L. perenne* | | 0.734* | 0.014 |
| | *P. pratensis* | Zn | 50.836* | 0.005 |
| | *A. stolonifera* | | 55.957* | 0.002 |
| | *L. perenne* | | 61.328* | 0.001 |
| | *F. arundinacea* | | 66.777* | 0.000 |
| | *F. rubra* | | 72.405* | 0.000 |
| *A. canina* | *P. pratensis* | Cd | 0.616 | 0.035 |
| | *F. rubra* | | 0.618 | 0.036 |
| | *L. perenne* | | 0.662 | 0.025 |
| | *P. pratensis* | Zn | 36.511 | 0.037 |
| | *A. stolonifera* | | 41.633 | 0.019 |
| | *L. perenne* | | 47.004 | 0.009 |
| | *F. arundinacea* | | 52.453 | 0.004 |
| | *F. rubra* | | 58.091 | 0.002 |

### B: Significant Post Hoc Results for the 5g Street Dust Treatment

| Species (I) | Species (J) | Heavy Metal | Mean Difference (I-J) | Sig. |
|---|---|---|---|---|
| *A. capillaris syn.tenuis* | *L. perenne* | Ni | 813.256* | 0.043 |
| | *P. pratensis* | | 817.952* | 0.042 |
| | *F. arundinacea* | | 871.249* | 0.033 |
| | *F. rubra* | | 878.964* | 0.030 |
| *A. canina* | *P. pratensis* | Cu | 15.518 | 0.030 |
| | *A. capillaris syn.tenuis* | | 18.678* | 0.010 |
| | *A. stolonifera* | | 24.216* | 0.001 |
| | *L. perenne* | | 24.826* | 0.001 |
| | *F. rubra* | | 26.023* | 0.001 |
| | *A. capillaris syn.tenuis* | Ni | 861.967* | 0.033 |
| | *L. perenne* | | 1675.222* | 0.000 |
| | *P. pratensis* | | 1679.918* | 0.000 |
| | *A. stolonifera* | | 1689.263* | 0.000 |
| | *F. arundinacea* | | 1733.216* | 0.000 |
| | *F. rubra* | | 1740.930* | 0.000 |
| | *A. capillaris syn.tenuis* | Zn | 91.828 | 0.000 |
| | *P. pratensis* | | 95.075 | 0.000 |
| | *A. stolonifera* | | 100.267 | 0.000 |
| | *L. perenne* | | 117.954 | 0.000 |
| | *F. arundinacea* | | 127.819 | 0.000 |
| | *F. rubra* | | 129.027 | 0.000 |

## C: Significant Post Hoc Results for the 10g Street Dust Treatment

| Species (I) | Species (J) | Heavy Metal | Mean Difference (I-J) | Sig. |
|---|---|---|---|---|
| *A. canina* | *P. pratensis* | Cu | 45.058* | 0.000 |
| | *L. perenne* | | 60.203* | 0.000 |
| | *A. stolonifera* | | 60.290* | 0.000 |
| | *F. rubra* | | 60.968* | 0.000 |
| | *A. capillaris syn.tenuis* | | 61.647* | 0.000 |
| | *F. arundinacea* | | 64.605* | 0.000 |
| | *A. capillaris syn.tenuis* | Ni | 3877.085* | 0.000 |
| | *L. perenne* | | 4014.450* | 0.000 |
| | *A. stolonifera* | | 4024.819* | 0.000 |
| | *P. pratensis* | | 4048.109* | 0.000 |
| | *F. rubra* | | 4062.065* | 0.000 |
| | *F. arundinacea* | | 4096.752* | 0.000 |
| | *P. pratensis* | Pb | 18.581 | 0.000 |
| | *L. perenne* | | 21.354* | 0.000 |
| | *F. rubra* | | 22.367* | 0.000 |
| | *A. capillaris syn.tenuis* | | 22.498* | 0.000 |
| | *A. stolonifera* | | 22.538* | 0.000 |
| | *F. arundinacea* | | 22.929* | 0.000 |
| | *A. capillaris syn.tenuis* | Zn | 91.828 | 0.000 |
| | *A. stolonifera* | | 117.689* | 0.000 |
| | *L. perenne* | | 117.954* | 0.000 |
| | *F. arundinacea* | | 127.819* | 0.000 |
| | *F. rubra* | | 129.027* | 0.000 |
| | *A. capillaris syn.tenuis* | | 91.828* | 0.000 |
| | *P. pratensis* | | 95.075* | 0.000 |

## D: Significant Post Hoc Results for the 20g Street Dust Treatment

| Species (I) | Species (J) | Heavy Metal | Mean Difference (I-J) | Sig. |
|---|---|---|---|---|
| *A. capillaris syn.tenuis* | *F. arundinacea* | Cu | 7.134 | 0.044 |
| | *A. stolonifera* | Ni | 1275.420 | 0.000 |
| | *L. perenne* | | 1394.403* | 0.000 |
| | *P. pratensis* | | 1441.933* | 0.000 |
| | *F. rubra* | | 1448.355* | 0.000 |
| | *F. arundinacea* | | 1460.883* | 0.000 |
| | *L. perenne* | Zn | 17.305 | 0.033 |
| | *A. stolonifera* | | 18.021* | 0.033 |
| | *F. rubra* | | 29.670* | 0.001 |
| | *F. arundinacea* | | 32.035* | 0.000 |
| *L. perenne* | *F. arundinacea* | Pb | 2.216* | 0.029 |
| | *A. capillaris syn.tenuis* | | 2.337* | 0.022 |
| *P. pratensis* | *A. capillaris syn.tenuis* | Cu | 9.791 | 0.007 |
| | *L. perenne* | | 10.721* | 0.004 |
| | *F. rubra* | | 10.933* | 0.003 |
| | *A. stolonifera* | | 12.351* | 0.001 |
| | *F. arundinacea* | | 16.931* | 0.000 |
| | *L. perenne* | Pb | 3.087* | 0.003 |
| | *F. rubra* | | 4.545* | 0.000 |
| | *A. stolonifera* | | 4.813* | 0.000 |
| | *F. arundinacea* | | 5.303* | 0.000 |
| | *A. capillaris syn.tenuis* | | 5.423* | 0.000 |
| | *L. perenne* | Zn | 20.919* | 0.015 |
| | *A. stolonifera* | | 21.635* | 0.012 |
| | *F. rubra* | | 33.284* | 0.000 |
| | *F. arundinacea* | | 35.649* | 0.000 |
| *A. canina* | *A. capillaris syn.tenuis* | Cd | 1.769* | 0.015 |
| | *F. arundinacea* | | 2.072* | 0.005 |
| | *P. pratensis* | | 2.146* | 0.004 |
| | *A. stolonifera* | | 2.149* | 0.004 |
| | *F. rubra* | | 2.182* | 0.003 |
| | *L. perenne* | | 2.202* | 0.003 |
| | *A. capillaris syn.tenuis* | Cu | 15.325* | 0.000 |
| | *L. perenne* | | 16.255* | 0.000 |
| | *F. rubra* | | 16.466* | 0.000 |
| | *A. stolonifera* | | 17.885* | 0.000 |
| | *F. arundinacea* | | 22.464* | 0.000 |
| | *A. stolonifera* | Ni | 1695.920* | 0.000 |
| | *L. perenne* | | 1814.903* | 0.000 |
| | *P. pratensis* | | 1862.433 | 0.000 |
| | *F. rubra* | | 1868.855* | 0.000 |
| | *F. arundinacea* | | 1881.383* | 0.000 |
| | *L. perenne* | Pb | 4.015 | 0.001 |
| | *F. rubra* | | 5.474* | 0.000 |
| | *A. stolonifera* | | 5.742* | 0.000 |
| | *F. arundinacea* | | 6.231* | 0.000 |
| | *A. capillaris syn.tenuis* | | 6.352* | 0.000 |
| | *P. pratensis* | Zn | 22.819* | 0.012 |
| | *A. capillaris syn.tenuis* | | 26.433* | 0.004 |
| | *L. perenne* | | 43.738* | 0.000 |
| | *A. stolonifera* | | 44.454* | 0.000 |
| | *F. rubra* | | 56.103* | 0.000 |
| | *F. arundinacea* | | 58.468* | 0.000 |

## E: Significant Post Hoc Results for the 40g Street Dust Treatment

| Species (I) | Species (J) | Heavy Metal | Mean Difference (I-J) | Sig. |
|---|---|---|---|---|
| A. capillaris syn.tenuis | *F. arundinacea* | Cd | 1.353 | 0.007 |
| | *P. pratensis* | | 1.476 | 0.004 |
| | *A. stolonifera* | | 1.5140 | 0.003 |
| | *F. rubra* | | 1.526 | 0.003 |
| | *L. perenne* | | 1.527 | 0.003 |
| | *L. perenne* | Cu | 20.539 | 0.043 |
| | *A. stolonifera* | | 22.602 | 0.027 |
| | *F. arundinacea* | | 26.762 | 0.015 |
| | *A. stolonifera* | Ni | 2493.028 | 0.000 |
| | *L. perenne* | | 2525.989 | 0.000 |
| | *F. arundinacea* | | 2580.583 | 0.000 |
| | *F. rubra* | | 2581.116 | 0.000 |
| | *P. pratensis* | | 2598.892 | 0.000 |
| | *F. arundinacea* | Zn | 36.628 | 0.012 |
| | *F. rubra* | | 38.655 | 0.012 |
| *A. canina* | *F. arundinacea* | Cd | 1.170 | 0.025 |
| | *P. pratensis* | | 1.293 | 0.014 |
| | *F. rubra* | | 1.342 | 0.011 |
| | *A. stolonifera* | | 1.331 | 0.012 |
| | *L. perenne* | | 1.344 | 0.011 |
| | *P. pratensis* | Cu | 28.332 | 0.010 |
| | *F. rubra* | | 33.685 | 0.002 |
| | *L. perenne* | | 34.663 | 0.001 |
| | *A. stolonifera* | | 36.726 | 0.001 |
| | *F. arundinacea* | | 40.886 | 0.000 |
| | *A. capillaris syn.tenuis* | Ni | 1307.765* | 0.003 |
| | *A. stolonifera* | | 3800.793 | 0.000 |
| | *L. perenne* | | 3833.754 | 0.000 |
| | *F. arundinacea* | | 3888.347 | 0.000 |
| | *F. rubra* | | 3888.881 | 0.000 |
| | *P. pratensis* | | 3906.656 | 0.000 |
| | *A. capillaris syn.tenuis* | Zn | 60.712 | 0.000 |
| | *P. pratensis* | | 65.931 | 0.000 |
| | *L. perenne* | | 82.110 | 0.000 |
| | *A. stolonifera* | | 85.125 | 0.000 |
| | *F. arundinacea* | | 97.340 | 0.000 |
| | *F. rubra* | | 99.367 | 0.000 |